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Optics and Fluid Dynamics Department Annual Progress Report for 1992

Edited by L. Lading, J.P. Lynov, and B. Skaarup

Risø National Laboratory, Roskilde, Denmark
January 1993

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Abstract

Research in the Optics and Fluid Dynamics Department is performed within two sections. The Optics Section has activities within (a) optical materials, (b) quasi-elastic light scattering and diagnostics in solids, fluids and plasmas, and (c) optical and electronic information processing. The Continuum Physics Section performs (a) studies of nonlinear dynamical processes in continuum systems, (b) investigations of other problems in fusion plasma physics, and (c) develops pellet injectors for fusion experiments. Most of these activities are done in connection with the Euratom Association. A summary of activities in 1992 is presented.

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Contents

1 Introduction

The department performs basic and applied research within continuum physics and optics. The scope is both understanding of physical phenomena and development of materials and systems for specific applications. The activities are often performed in collaboration with other research groups and industry. The training of students at a graduate level is an integral part of the activities and so is the dissemination of the results to research and industry. The results are important for the understanding of the dynamics of fluids including fusion plasmas, as well as for the understanding of optical diagnostic systems and new optical materials. Several of the results are exploited by industry.

It may be surprising to encounter optics, fluid dynamics, and plasma physics in one relatively small department. The motivation for this particular combination of disciplines is that most of the activities lie within what can be called continuum physics. Several of the basic theoretical tools are similar. In addition to this fact most of the optical work on diagnostics/measurement science is concentrated on fluid applications.

The work described in this report falls within the following categories:

- *Continuum physics* is concentrated on basic physical phenomena with relevance to fusion in plasmas as well as to other fluid dynamic systems. Coherent structures, turbulent transport, and general nonlinear phenomena are investigated. Both theoretical, numerical, and experimental work is performed. A significant effort is devoted to the development of efficient reliable spectral models investigated on computers. Experimental work is performed in turbulent plasmas and in shallow rotating water flows.
- *Pellet injection* systems have been developed and are now delivered to other fusion research laboratories. Work is also performed on the pellet plasma interaction.
- *Optical materials and light propagation* are concentrated on nonlinear phenomena, storage materials, and propagation in random media.
- *Diagnostic methods* for probing the state of both fluid mechanical systems and systems based on solids are investigated.
- *Optical and electronic information processing* incorporates work on two-dimensional optical transforms applied to pattern recognition. Schemes for proper data reduction and neural networks are also investigated.

Of major results in 1992 can be mentioned:

- New storage and nonlinear phenomena in liquid crystal polyesters were discovered.
- A novel nonlinear hybrid optical and electronic filtering scheme was implemented.
- A scheme for implementing tunable interference filters in photorefractive material was conceived.
- New schemes for space-time processing to measure size, displacement, and velocity were conceived and verified.
- Close agreement was found between experimental and numerical results for complex interaction processes between coherent structures and boundary layers near walls in two-dimensional flows.

- New numerical and experimental results were obtained for the development of coherent structures in anisotropic systems.
- Contracts were signed for construction of pellet injector systems to the Italian fusion programme.

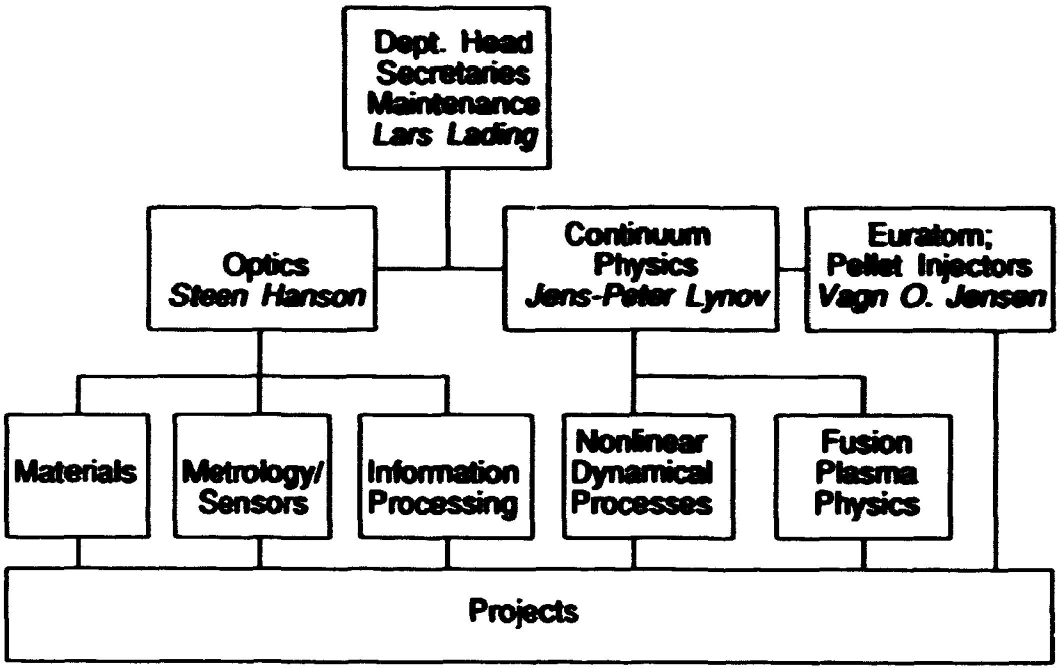

Figure 1. Organisation of the Optics and Fluid Dynamics Department.

2 Optics Section

2.1 Introduction

The activities of the section have been performed within three major areas:

- *Optical materials*
  The emphasis is here on materials and systems for storage and processing of spatial information.
  Organic materials with special properties for information storage and processing are investigated. Some unique storage properties of liquid crystal polyesters have been discovered.
  Dichromated gelatin is well established for recording of thick phase holograms. However, the reproducibility of the recording process has been a problem. This was investigated in a so-called industrial Ph.D. project jointly with an industrial partner. Several of the essential chemical and physical processes involved were identified and it was established how they are controlled. Computer-generated holograms are essential for several of the activities in the section. A novel laser plotting system has been developed that makes it possible directly to record holograms with very high resolution and also with grey scales.
  Photorefractive materials are well established for dynamic recording of volume holograms. The section has worked on models for the basic physical properties of photorefraction. It has been shown how magnetic fields affect the nonlinear properties; also within the area of photorefraction: a novel scheme for controllable interference filters has been devised. This is now subjected to further investigations.

- *Optoelectronic sensors*
  For a number of years the section has investigated and developed several systems for probing the dynamic properties of fluids and solids based on quasi-elastic light scattering.
  Time-of-flight velocimetry for the measurement of the velocity of solid objects based on speckle correlation has been investigated. Effects of focusing/misfocusing on the correlation function and the measurement uncertainty have been investigated. It has also been shown that nonlinear processing can reduce the generally used lower limits to the uncertainty. It has furthermore been demonstrated how the time-of-flight principle can be extended so that also the size of spherical particles can be measured.
  Speckle interferometry is well established for the absolute measurement of displacements/vibrations. Schemes for measuring relative displacements have been devised. In all such systems the effects of speckle decorrelation are very important. A rigorous analysis of decorrelation effects has been performed.
  Several schemes for measuring displacements and velocity based on special spatial filters and holograms have been investigated. In some systems partly incoherent light sources may be applied. Spatial filters may then facilitate desired spatial coherence properties.

- *Information processing*
  Information processing involves both optical and electronic methods. The use of neural network concepts has increased in the last couple of years.
  A novel nonlinear optoelectronic loop for nonlinear filtering of noisy images has been demonstrated.
  Neural network processing is applied in a project on automatic evisceration of pigs. The section has developed an image processing concept for identification and control in connection with noisy objects with varying size and form.

Neural networks are also applied for optical recognition of handwritten characters. A network developed in the section was used in the NIST "consensus conference". The Risø system performed quite well among the systems that did not apply a special preprocessing scheme.
The direct processing of particle image velocimetry data has been investigated in the case of very low light levels. Photon counting is assumed and it has been verified that earlier developed very fast correlation methods can be applied.

2.2 Optical Materials

2.2.1 Erasable optical information storage

(P. S. Ramanujam, L. R. Lindvold, S. Hvilsted (Materials Department), and F. Andruzzi (CNR, University of Pisa, Italy))

There is an ever-increasing demand for efficient fleeting short-term and permanent long-term optical memories. Short-term memories are mainly used as volatile RAMs in spatial light modulators in optical correlation systems. Permanent storage of digital information encoded as bits can be used in archives as well as in audiovisual entertainment systems while storage of a large number of holograms would be beneficial in page-oriented memories and teaching image libraries. It is desirable that the information be retrieved quickly and be capable of total erasure and rerecording. Further desirable requirements for these materials include short response times, high resolution (>1000 lines/mm), no wet processing, no fatigue in the materials during repeated storage, and no erasure on repeated readouts combined with high read efficiency. Currently, no material fulfilling all these criteria exists.

We have recently been funded by ESPRIT-Basic Research programme ("Parallel Optical Processing and Memories" - Project No. 6863) to investigate the properties of a biological molecule, bacteriorhodopsin for short-term optical storage. Bacteriorhodopsin has recently been used for second harmonic generation, dynamic holography, phase conjugation, as holographic memory in optical neural networks, and as spatial light modulators for nonlinear optical filtering. After excitation with yellow light at 570 nm, the ground state of bacteriorhodopsin (Fig. 1) cycles through a few short-lived intermediate states to end up in the M state which has a natural lifetime of about 10 ms. This state can also relax back to the B state photochemically upon excitation with blue light at 412 nm. This material exhibits extreme photochemical stability and can be cycled between the B state and the M state several hundred thousand times without experiencing fatigue. The lifetime of the intermediate state is strongly dependent on the humidity and pH of the surroundings.

The existing concepts for erasable long-term storage are based upon magneto-optic rotation in thin films or thermal phase changes due to local heating generated by a focused laser beam. Side-chain liquid crystalline polyesters show great promise as erasable media for optical information storage. They exhibit high diffraction efficiency and durability and require low power. These polyesters consist of cyanoazobenzene moities in the side-chain linked by means of a flexible spacer to the main chain polyester. They exhibit good mechanical properties with excellent fibre and film forming capabilities. We have been able to record holograms with a resolution greater than 5000 lines/mm on unoriented films of side-chain liquid crystalline polyesters. Recording energies of about 1 J/cm^2 have been used. Diffraction efficiencies greater than 30% have been achieved using polarisation recording of holograms. Holograms recorded about eight months ago show no sign of decay in the diffraction efficiency. The holograms can be erased by heating them to approximately 85° C and are available for rerecording. By varying the length of the acidic constituent of the main chain we have been able to observe novel biphotonic processes in these materials. Gratings generated through the interference of an argon laser beam are fixed in the materials by the light from a red laser. These holograms have a typical efficiency of about 15% with a typical size of 1 mm corresponding to the size of the laser beam. One interesting aspect of the recording is that one could wait for several minutes between the exposures of the argon laser beam and the red laser beam. We believe that these materials have a great potential as holographic interconnects in an optical neural network.

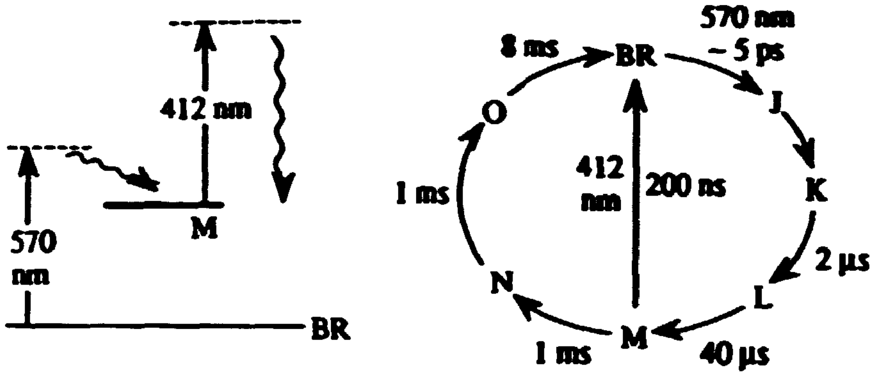

Figure 1. Bacteriorhodopsin energy states.

2.2.2 Measurements of the bulk parameters of dichromated gelatin

(L. R. Lindvold)

Dichromated gelatin (DCG) is extensively used by the department as a volume phase recording material for use in holographic optical elements. The chemistry of the recording material has, however, caused some problems in terms of the reproducibility of the DCG films. A Ph.D. project addressing these problems was completed in 1992, in collaboration with Dantec Measurement Technology A/S and Physics Laboratory I at the Technical University of Denmark.

It was found that two basic processes involved in the formation of phase gratings in DCG films could be simulated in bulk samples of dichromate and gelatin solutions, respectively:

- The photoinduced conversion of Cr(VI) into Cr(III) that crosslinks certain aminoacids of the polypeptide chain in the gelatin and thus forms the "latent image" in the DCG film.
- The intrinsic prehardening of the DCG film, i.e. the hardening taking place prior to the actinic exposure. This parameter is of interest because it strongly affects the maximum attainable diffraction efficiency as well as the scattering from the processed hologram.

The former process can be monitored by measuring the photoinduced redox potential in a dichromate solution, and the latter by rheometric measurements of the gelatin's modulus of rigidity. The use of these methods enables us to relate some of the bulk properties of the dichromated gelatin to its sensitometric properties. This is of great value as screening methods in the development of new formulations.

The photoinduced redox potential of water-soluble dichromates was measured as a function of various parameters using the setup depicted in Fig. 1a. Using this technique, the following parameters were found to affect the sensitivity of DCG, viz. different electron donors, cations like K^+, Na^+, NH_4^+ (cf. Fig. 1b), and water. It is anticipated that the effect of dye sensitisation of DCG film can be studied by this technique also.

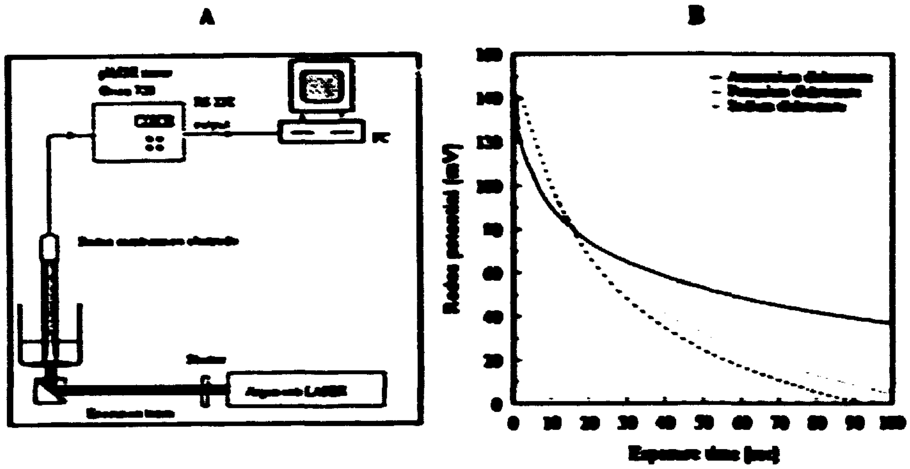

Figure 1. a) Setup for measuring the photoinduced redox potential in a dichromate solution. b) The influence of the cation on the photosensitivity of the dichromate ion.

Gelatin's swelling properties are generally related to a number of physical and chemical parameters. One of these parameters, the intrinsic crosslinking of the gelatin, is affected by the gelatin concentration of the casting solution and the drying time during the casting process of the DCG film. The crosslinking of the gelatin is reflected by the resilience of the gel, often characterised by the Bloom number. The determination of the Bloom number is, however, very time consuming (16 hours). In order to avoid this lengthy test method, a cone-and-plate rheometer, which is available at the Polymer Chemistry Section in the Materials Department, has been used instead. This makes it possible to perform the test in two hours and still obtain results that are in agreement with the Bloom number.

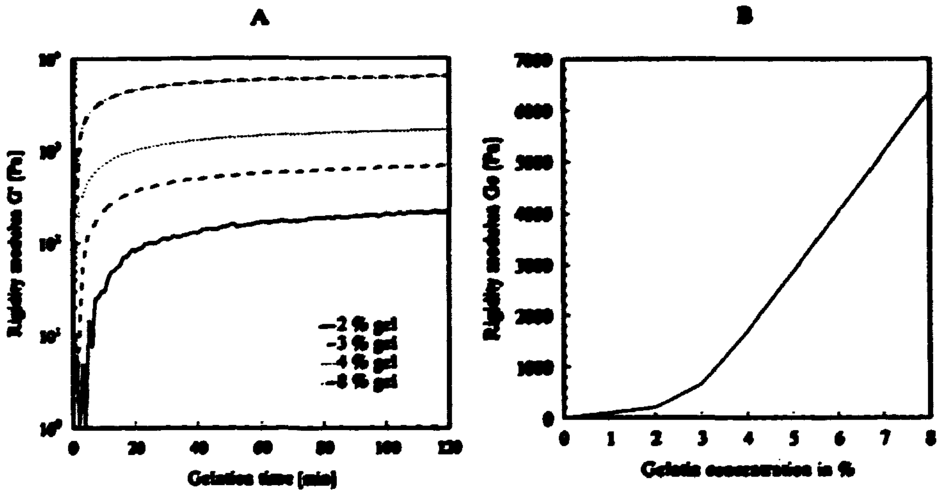

Figure 2. a) Gel rigidity at different concentrations @ T = 283 K. b) Gel rigidity after 2 hours' gelation @ T = 283 K as a function of gelatin concentration.

The resilience of a gel at different gelatin concentrations, ranging from 2 to 8 w/v % has been made. The plot of this series of measurements is shown in Fig. 2a. The end values at $t = 2$ hours have been plotted in Fig. 2b. It can be inferred that the gelatin concentration has a strong influence on the bias hardness of the gelatin. This is of interest to our work as we adjust the thickness of the DCG films by altering the gelatin concentration. The findings explain discrepancies in previous results with DCG films having thicknesses from 20 to 70 μm. As a consequence of these tests new coating methods will be examined in the future to solve this problem.

2.2.3 Holoplotter

(E. Rasmussen, A. Skov Jensen, and E. Eilertsen)

For several years computer-generated holograms have been an integral part of the activities in the section. Initially a modified satellite recorder was used for plotting the masters for the holograms. However, neither resolution nor the format was compatible with the requirements given by the designed holograms. Thus it was decided to develop a dedicated plotter. The capacity should be at least 36 million points (pixels), a resolution of 10 μm x 10 μm, and 64 grey scales. The plotter is currently implemented with a HeNe laser. An acoustooptic cell is used for modulation and a special high resolution interferometric system is used for controlling the spot position. Tests with the system indicate that the resolution may be enhanced by a factor of 4 and the number of spots by more than an order of magnitude. Holograms for both neural network applications and for optical sensors have been made with the new plotter. The project has been partly supported by the National Agency of Industry and Trade.

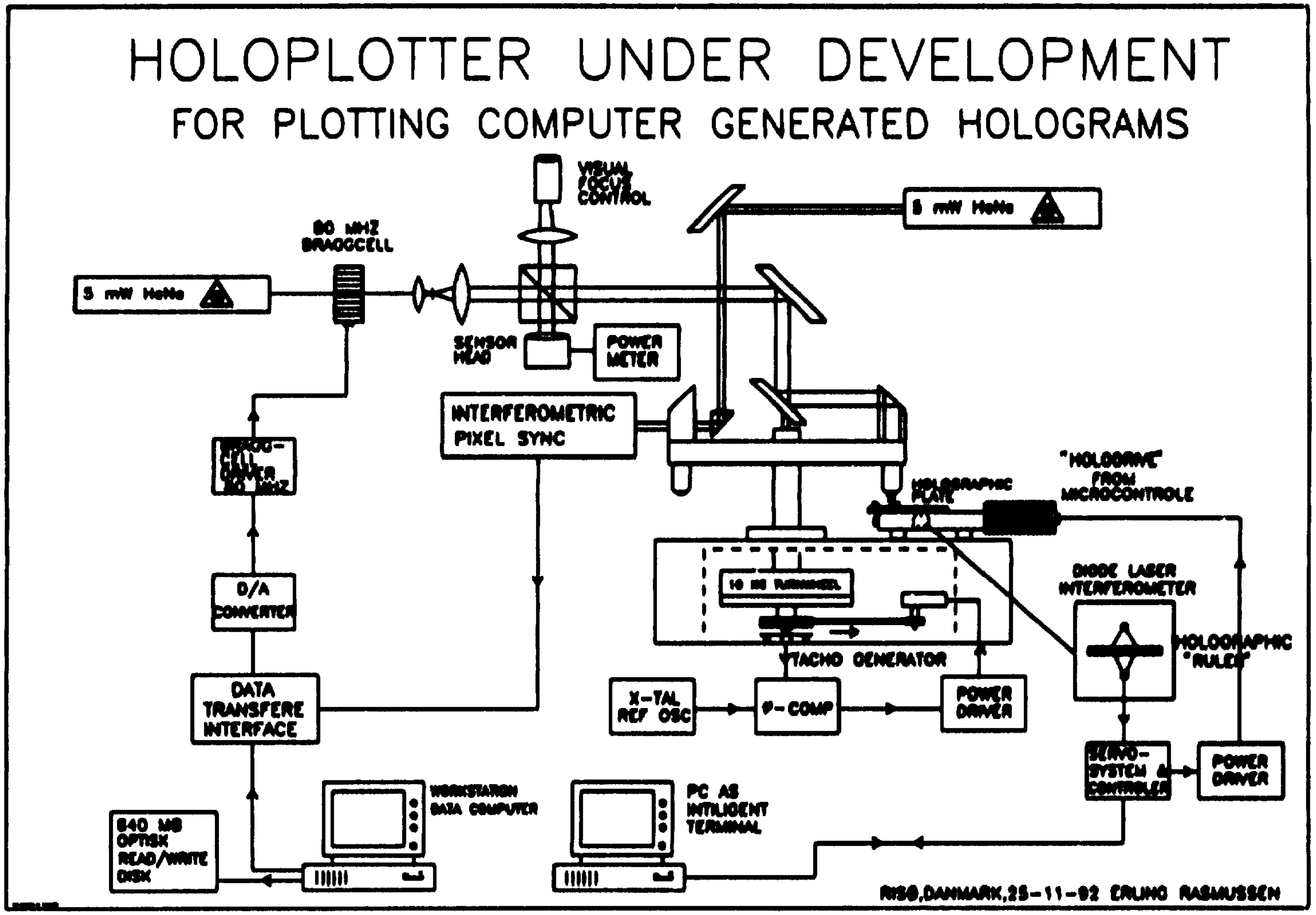

Figure 1. Layout of a system for direct recording of computer-generated holograms.

2.2.4 Magnetic interactions in photorefractive media

(P. M. Johansen)

The existing formulation of two-beam coupling in photorefractive media has been extended to include the effects of an external magnetic field via the introduction of the Faraday effect which rotates the state of polarisation of the incident laser fields proportional to the magnitude of the magnetic field component along the direction of propagation of the fields. The effect of the magnetic field on the material refractive index is also taken into account. It is shown that the presence of such a magnetic field causes oscillations in the two-beam coupling strength of the material even in the case of materials with no optical activity. Furthermore, it is shown that the direction of the Faraday effect can be controlled by controlling the direction of the externally applied magnetic field and, hence, in very favourable situations cancel the effect of optical activity and thereby strengthen the optical coupling between the two beams interacting in the nonlinear material.

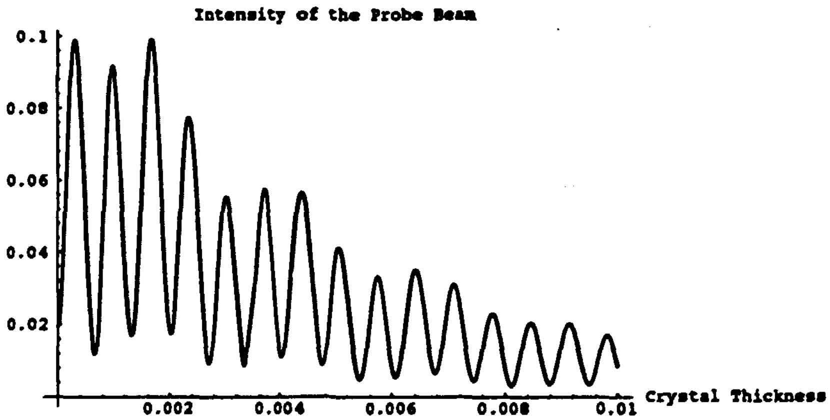

Figure 1. The figure shows the oscillations in the intensity of the weak beam in two-wave mixing in photorefractive GaAs:Cr under the influence of an externally applied static magnetic field.

1) Johansen, P. M. and Jensen, A. S. (1991). J. Opt. Soc. B. 8, 2342-2354.

2.2.5 Photorefractive interference filters

(P. M. Johansen and P. M. Petersen (The Technical University of Denmark))

A new type of interference filters generated in photorefractive materials has been investigated. Such filters have very high wavelength selectivity as compared with ordinary dielectric mirrors and offer several external control parameters. The filter is written by two coherent laser beams incident to the photorefractive crystal of, e.g., $BaTiO_3$. Such two laser fields induce a periodic change, with periodicity Λ, in the refractive index of the material. A third beam incident to the crystal face experiences varying layers of high and low index of refraction. The situation experienced by this beam is analogous to that experienced in a multilayer dielectric mirror with alternating quarterwave layers of high and low index of refraction. In the present situation, however, the layer thickness is $\Lambda/2$. If this thickness is equal to a quarter of a wavelength for this laser field, the reflected wave from all layers will interfere constructively at the front surface of the crystal, and a strong reflected signal from the filter is obtained. The theory for conventional interference filters has been extended to include the generic type of photorefractive filters. It is shown that the reflectivity can be controlled externally by changing the angle between the two laser fields writing the periodic index variation and by changing the relative strength of these beams (changing the optical modulation). It is shown that with such filters it is possible to obtain a reflectivity which approaches unity and, furthermore, the filter characteristics can be adjusted in real time. This work is a joint project between Risø and The Technical University of Denmark.

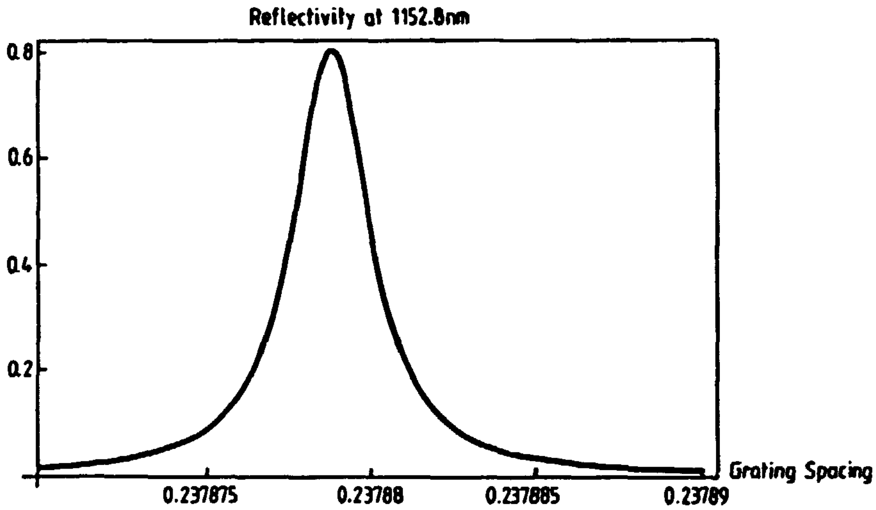

Figure 1. The curve shows the very narrow reflection versus the periodicity in the refractive index in photorefractive barium titanate.

1) Johansen, P. M. and Petersen, P. M. (1992). Nonlinear Optics: Materials, Fundamentals and Applications Technical Digest, (Optical Society of America, Washington, D.C., 1992), Vol. 18, 322-324.

2.3 Optoelectronic Sensors

2.3.1 Time-of-flight velocimetry

(S. Hanson, L. Lading, and H.T. Yura (Electronics Technology Center, The Aerospace Corporation, U.S.A))

Within the framework of complex ABCD matrices analytical solutions to the time-of-flight velocimetry system have been found. The cross-covariance for a defocused optical system has been given as a function of the system parameters including the apertures.

The sensitivity of the cross-covariance to various deviations in the target translation has been addressed and, consequently, analytical expressions have been found revealing the robustness of a given system. Misalignment of the target velocity with respect to the line joining the two illuminated spots will call for a reduction of the cross-covariance as will a tilt of the target as it proceeds from one illuminated spot to the next. The decrease in signal as a function of the parameters of a general optical system has been found.

Based on the determination of the centre position of the cross-covariance the minimum variance in the estimation of the velocity has been found. This provides a closed analytical expression for the error in velocity estimation using a time-of-flight laser anemometer. Within the framework of the ABCD system the complex matrix elements for an optical system will provide the necessary information for determining the basic limitations and sensitivities, given the referenced expressions.

Laser Doppler anemometry is well established for localised velocity measurements in fluids. The time-of-flight or two-spot principle has been applied in cases where extreme spatial selectivity is needed. However, the method may also have advantages when measuring the velocity of solid surfaces. A crosscorrelation processing is then needed. The fundamental limits to the measuring accuracy – or rather uncertainty – have been investigated. It has been proved that the traditional limitation based on the simple time bandwidth considerations does not represent fundamental limits. If no photon noise appears in the signal and a Gaussian intensity distribution is assumed for the illuminating beams (or some other distribution that is not absolutely truncated), an arbitrarily high accuracy can be achieved by amplifying the high frequency components of the signal and attenuating the low frequency components. For actual systems there is always an absolute truncation – a finite aperture – and this aperture defines the ultimate accuracy. A correlation exclusively based on the zero crossings may in cases of a frozen pattern hypothesis also give an arbitrarily low uncertainty. The impact of photon/electron noise on the minimum variance has also been evaluated. The optimum processing scheme does depend strongly on the statistics of the signal.

1) Yura, H.T. and Hanson, S.G., (1992). Laser Time-of-Flight Velocimetry: Analytical Solution to the Optical System Based on ABCD Matrices, to appear in Journal of The Optical Society of America at the end of 1993.

2.3.2 Particle sizing by pulse displacement measurements

(L. Lading and B. Hurup Hansen)

An image of a particle illuminated with a laser beam will in general be quite different from the geometrical optical image that is obtained with diffuse light. This is because a spherical particle that interacts with light will cause a spatially well defined phase perturbation of the electromagnetic field. This fact has for a number of years been utilised for particle sizing purposes with the phase-Doppler method. In such systems the size is inferred from a measurement of the phase difference between signals obtained from two different directions of detection. An alternative scheme may be based on measurements of the relative temporal positions of light pulses. A scheme for performing such measurements is shown in Fig. 1. When a particle passes the two well focused and closely spaced laser beams, it will give rise to the signals shown in Fig. 2. The large displacement gives the velocity and the smaller displacement gives the size. The fact that the size is given by the pulse displacement is simply caused by the fact that if the direction of detection is offset from the direction of incidence, then the maximum amount of collected light occurs when the particle is displaced a distance from the optical axis of the incident beam. The scheme shown here assumes that surface reflected light dominates. The scheme may also be applied in cases where the refracted light dominates. The diffractive (or birefringent) element shown in the filter plane ensures a desirable separation of the light pulses between the two detectors and maintains very good spatial selectivity.

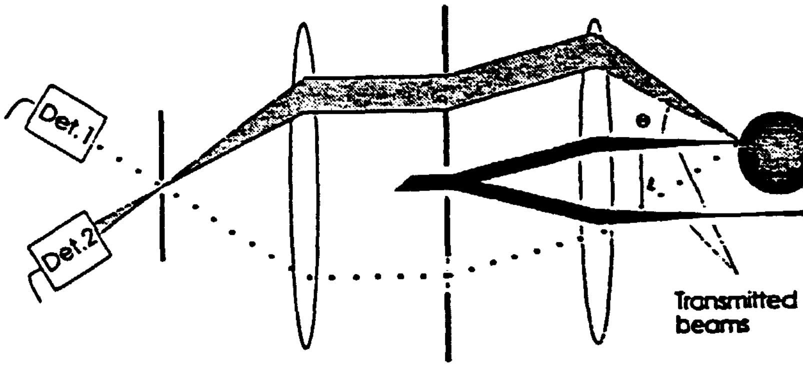

Figure 1. Optical configuration for measuring particle velocity and size by pulse displacements. The filter selecting the directions of detection does also contain a double refracting or diffracting element in order to ensure the wanted appearance of the pulses on the two detectors.

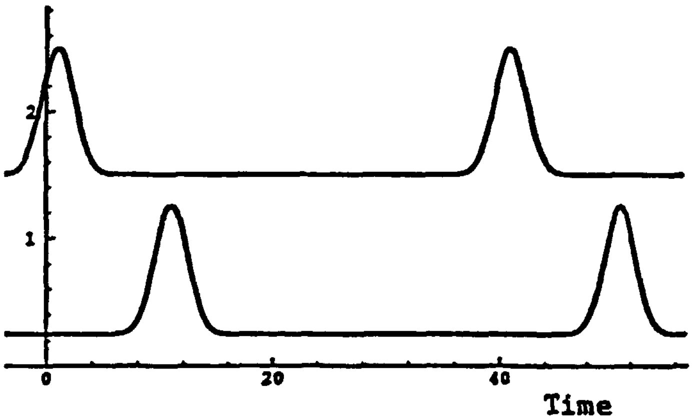

Figure 2. Sets of pulses from the two detectors in Fig. 1 when a spherical particle passes the measuring volume. The large spacing is given by the velocity and the small spacing between the signals of the two detectors is given by the particle size.

The scheme has been experimentally verified and initial estimates of the measuring range have been established. Relative to the phase-Doppler scheme it appears that the present system may be preferable for larger particles (i.e. > 200 μm) and may also provide for a larger dynamic range with just two detectors. The system may be implemented with just a single diffractive (holographic) optical element.

1) Saffman, M. and Buchhave, P. (1984). Simultaneous Measurement of Size, Concentration and Velocity of Spherical Particles by a Laser Doppler Method. Proceedings of the Second International Symposium on Applications of Laser Anemometry to Fluid Mechanics, Lisbon, Portugal.

2) Lading, L. and Hansen, B. Hurup (1992). A Complementary Method for Simultaneous Measurement of Size and Velocity. Proceedings of 6th International Symposium on Applications of Laser Techniques to Fluid Mechanics and Workshop on Computers in Flow Measurements, Lisbon, 20-23 July 1992 (Universidade Tecnica de Lisboa, Lisbon, 1992).

2.3.3 Speckle interferometry

(S. Hanson, B. Hurup Hansen, and H.T. Yura (Electronics Technology Center, The Aerospace Corporation, U.S.A))

The determination of decorrelation is essential for all interferometric measurements in that it establishes the ultimate limits to the application of the techniques. To give a closed form approach to the issue and further deal with general speckle characteristics, the previously presented complex ABCD formalism has been employed.

The use of complex ABCD ray matrix elements permits modelling of limiting apertures (e.g. thin lens, field stops, and finite sized measurement apertures) as soft (i.e. Gaussian) apertures. In many applications (e.g. imaging and Fourier transform systems) such modelling yields useful engineering analytical approximations to system performance that can be used for designing, sizing, and scaling of optical systems. In addition the results can generally be cast in a physical intuitive form where, for example, the effects of geometric optics and diffraction are readily apparent.

We have considered homogeneous media and have derived expressions for the mean, variance, and corresponding correlation function of the irradiance distribution resulting from an incoherent source that has propagated through a complex (axially symmetric) ABCD optical system. In particular, we obtain a general expression for the van Cittert-Zernike theorem to complex paraxial ABCD systems. We also present an expression that relates the number of speckle correlation cells contained within a measurement area to the parameters of the ABCD system. In particular, an expression for the maximum number of independent intensity measurements allowed by the optical system has been derived.

In speckle interferometry we have examined the effects of load induced object tilt around an in-plane axis, in-plane and out-of-plane object displacement on decorrelation of the interferograms operating in the subtraction mode. Analytical expressions for the limitations for various strains have been given in terms of the complex matrix elements, thus reducing the problem of future analysis of optical systems with respect to speckle decorrelation to a mere calculation of the complex matrix elements. The present work was financially supported by the Danish Technical Research Council.

1) Yura, H. T., Hanson, S. G., and Grum, T. P. (1992). Speckle Statistics and Decorrelation in Complex ABCD Optical Systems, to appear in Journal of The Optical Society of America, February 1993.

2.3.4 Measurement of sea surface parameters by light scattering

(S. Hanson and J. H. Churnside (NOAA Wave Propagation Laboratory, U.S.A))

The simultaneous emission of two mutually coherent laser beams along the same axis provides for the creation of a fringe pattern which moves at the velocity of light. The wave vector of the fringe pattern will be along the optical axis, and the fringe spacing will be given by the difference frequency of the two beams.

A system for probing capillary waves at the sea surface has been considered. The fringe pattern is projected down at the surface at a slanted angle, and reflections coming from either glints or scattering from submerged particles will be collected in a backscattering configuration. It can be shown that a resonance condition exists when the period of the surface wave equals half the period of the fringe pattern.

As the intensity pattern moves at the speed of light, the scattering particle can be considered fixed, and the backscattered signal will be modulated by the optical frequency plus a smaller amount given by the velocity of the resonance structure.

Establishing a system thus provides a means of probing the strength of the capillary waves on the surface and their phase velocities. Invoking the dispersion relation facilitates determination of the underlying current.

The polarisation effects have been considered besides the influence of the finite penetration depth of the light in the water. Optimal configurations have been identified and the effect of probing a two-dimensional distribution of capillary waves has been addressed.

1) Churnside, James H. and Hanson, Steen G. (1992). Delta-k LIDAR Calibration Factors, to be submitted to Applied Optics early in 1993.

2.3.5 Displacement invariant computer-generated filters

(S. Hanson, E. Rasmussen, and E. Eilertsen)

The section has developed a unique system for making computer-generated holograms both as absorption and phase holograms. This opens up for a variety of measurement schemes based on holographic optical elements (mentioned under "Optical Materials"). Conventional measurement systems mostly rely on having optical surfaces with linear and quadratic shapes giving rise to only a very limited amount of transformations. Nevertheless, a multitude of measurement systems have evolved founded on both coherent and incoherent light.

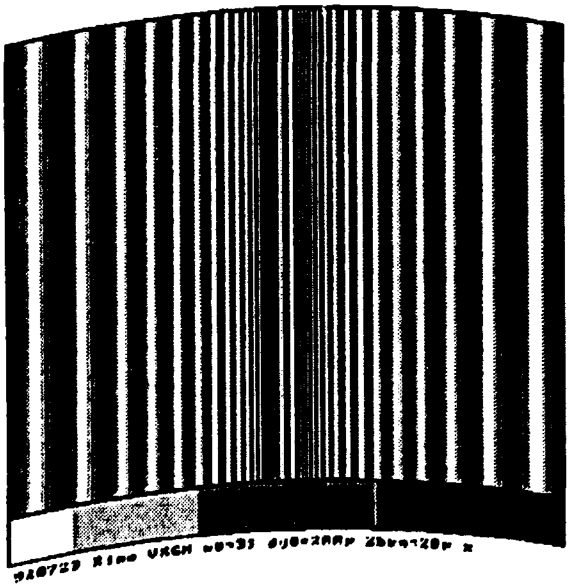

Figure 1. Computer-generated hologram made as linear logarithmic grating used for longitudinal self-imaging of planes of light.

Using computer-generated holograms facilitates a larger degree of freedom in the design of optical transducers. Where many coherent detection schemes are hampered by speckle noise, adequately shaping the spatial coherence of the initially spatially incoherent radiation may bring about a signal less affected by spatial noise. Any spatial filter will change the coherence properties of the transmitted light and, subsequently, spatially filtering of the transmitted and received light may provide for better measurement systems.

The use of succeeding spatial filters has been addressed with special emphasis on filters having translational and/or rotational invariance properties. Self-imaging aspects were theoretically and experimentally observed, and connections to possible future measurement systems were pointed out.

1) Hanson, S. Grüner (1992). Diffractive Optics: Design, Fabrication, and Applications. Diffractive Optics: Design, Fabrication, and Applications Topical Meeting, New Orleans, LA (US), 13-15 April 1992. (Optical Society of America, Washington, DC, 1992) (1992 Technical Digest Series 9), 123-125.

2.3.6 Measurement of optical turbulence by spatial filtering

(S. Hanson, J. H. Churnside*, and J. J. Wilson* (*NOAA, Wave Propagation Laboratory, U.S.A))

A system for wind velocity and refractive turbulence strength across an optical path using a natural light source has been proposed. The system is based on having a quasi-coherent light beam passing the vertical distribution of refractive turbulence. By introducing two spatial filters in conjunction with the detector system, it has been proved to be feasible to achieve a spatially resolved determination of the strength of the optical turbulence and one component of the horizontal velocity.

Laboratory experiments have been conducted and compared with analytical calculations of the signal parameters. A good agreement has been found which identifies the maximum altitude at which readings can be expected to be recovered.

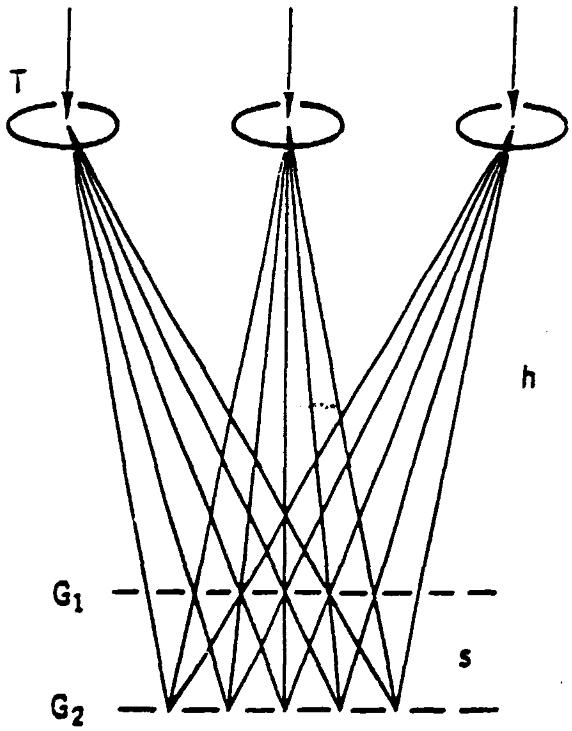

Figure 1. Ray diagram for double-spatial-filter configuration showing refractive scattering layer (T) at distance h and the two receiving gratings (G1 and G2) separated by distance s.

The basic measurement principle is delineated in Fig. 1 and shows the adopted "Moiré" concept.

The two measurement filters, here assumed to be absorption gratings, define a spatial period and an altitude at which "focusing" takes place. Having a matching structure at the correct altitude will cause the detector current to have a characteristic frequency given by the wavenumber of the scattering structure times its velocity component. The signal strength will be given by the strength of the refractive turbulence (C_n^2). The benefit of the system is that the detector gratings can be replaced by Bragg cells having high diffraction efficiencies. Further, the expected signal will be offset by the difference frequency of the driving signals to the Bragg cells which facilitates synchronous detection and velocity sign determination.

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2) Churnside, James H., Clifford, Steven F., and Hanson, Steen G. (1992). Single-Ended Dual Spatial Filter Detector for the Passive Measurement of Winds and Turbulence aloft, United States Patent 5, 159, 407, issued 27 October 1992.

2.4 Information Processing

2.4.1 An optoelectronic feedback loop for nonlinear filtering of images

(J. Glückstad and T. Martini Jørgensen)

A 4-f optical system incorporating a matched filter in the Fourier domain is well known as a Van der Lugt correlator. However, a matched filter based on a complete target pattern is very sensitive to small distortions and noise. To obtain a more robust scheme for recognition of specific patterns it has been suggested to use a bank of discriminating wavelet filters in the Fourier domain. But such a scheme might still have difficulties in coping with severe noise levels. To further increase the discrimination capability of this configuration it is advantageous to incorporate an annealing strategy.

We have constructed a novel optoelectronic feedback loop performing a parallel mean field annealing algorithm which we have developed to extract features characterised by a set of wavelets.

The iterative optimisation algorithm implemented by the loop is based on an interplay between a nonlinearity in the space domain and a linear filter in the Fourier domain of a 4-f configuration. A proper cost function describing the problem to be solved determines the filters to be used in the Fourier domain. Once the cost function is defined, an annealing strategy is used to escape from local minima. This corresponds to gradually increasing (i.e. at each iteration in the loop) the slope of the thresholding function used in the space domain. This bears a close analogy to the dynamics of the well-known spin-Ising model described in statistical mechanics.

The optical loop consists of a liquid crystal television displaying the image to be processed, a 4-f lens system containing the wavelet filter in the Fourier domain, a CCD-camera detecting the filtered image, and a framegrabber performing image addition and nonlinear thresholding. To overcome the stability problems inherent in an optical loop we have developed specific schemes to cope with the spatial and temporal inhomogeneities in light intensity as well as the geometric distortions introduced by misalignment.

The optical architecture is capable of extracting low level features in a noisy domain. Especially it should be possible to isolate coherent areas having common characteristics given by the chosen wavelet filters. Figs. 1 and 2 show the experimental results obtained by using a filter that favours low frequencies. With such a setup it is possible to extract low frequency structures which could not be extracted by use of a single lowpass filter and a single thresholding operation. Such a scheme could be used for defect detection.

Computer simulations show that it is also possible to discriminate more complex structures which only differ in their power distribution within the pass bands given by the wavelet filters.

1) Feature Issue on Wavelet Transforms (1992). Opt. Eng. 31, 1823-1916.

2) Hertz, J., Krogh, A., and Palmer, R.A. (1991). Neural Computation, (Addison-Wesley, Redwood City).

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a b

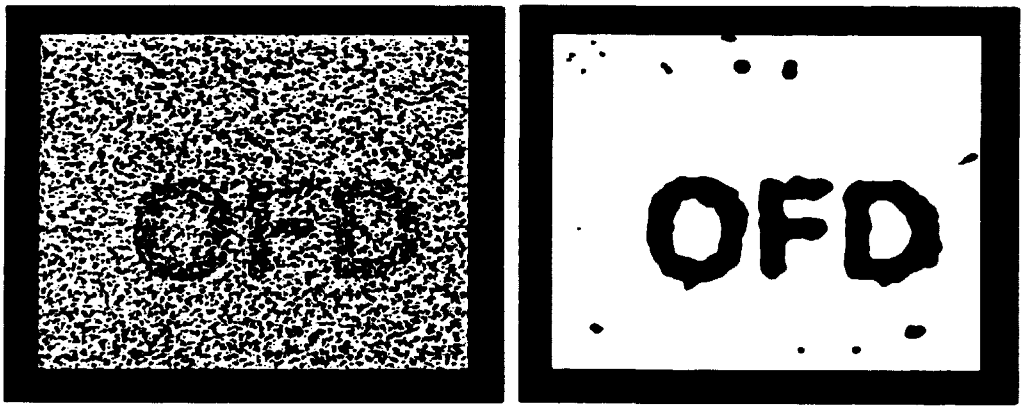

Figure 1. (a) shows an acronym with a modulation depth equal to 18 grey levels buried in Gaussian noise with a standard deviation corresponding to 20 grey levels. (b) shows the filtered output after 16 iterations.

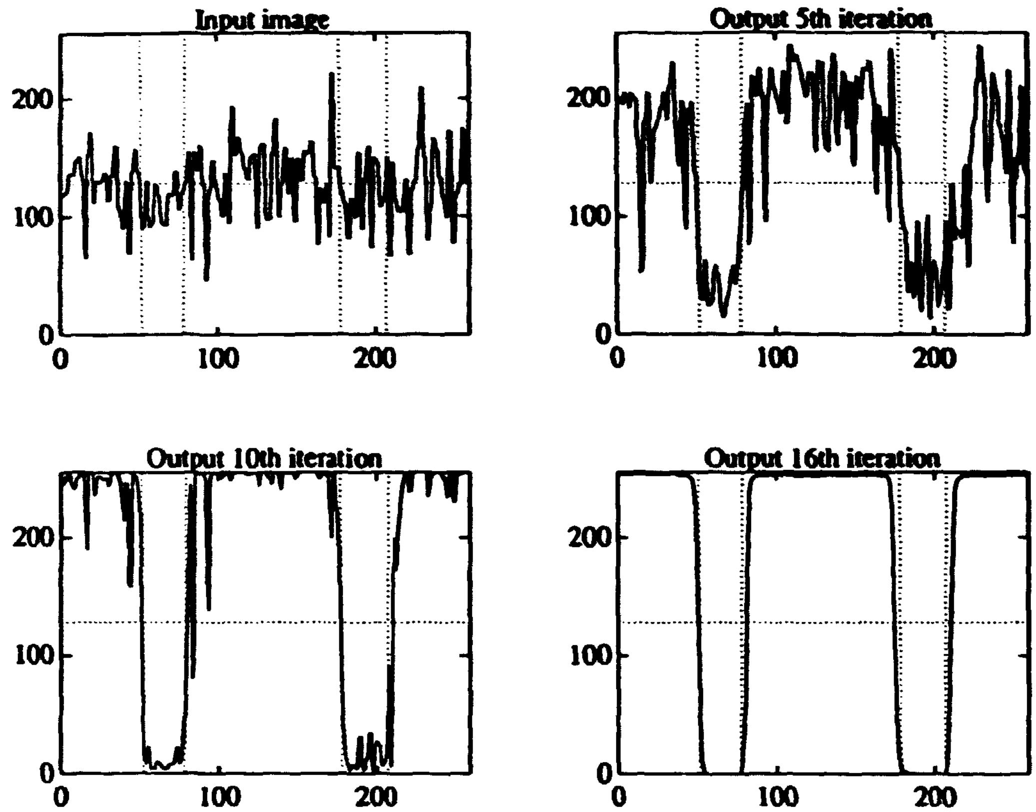

Figure 2. Vertical line profiles through the letter "F". The first profile is the input to the 1st iteration, whereas the following profiles correspond to the output of the 5th, the 10th, and the 16th iteration.

2.4.2 Development of sensing, controlling, and handling automation technology for separation of flexible food materials

(S. Sloth Christensen and Allan Andersen (Engineering and Computer Department))

The department participates in an EC BRITE project together with the Danish Meat Research Institute (DK), Bristol University (UK), Siemens AG (Germany), and Ricardo Hitec (UK). The purpose of the project is to automate the pig evisceration process in order to reduce the contamination of the pig meat. The evisceration process will be performed by a robot developed by Ricardo Hitec. The huge variances between pigs make it necessary to use an advanced sensor system to supply appropriate control data to the robot. It is the task of Risø to develop and implement the necessary image processing methods to satisfy these requirements.

Due to the complexity of the pig images it was decided to apply neural network (NN) methods to the image processing task. This approach ensures a high degree of noise robustness and the capability of coping with a wide range of pig types.

A new NN system developed at Risø is used to process the image data and locate feature points on the pig carcass. The advantage of this NN method is that the training time is considerably smaller than that of other comparable methods.

A prototype system has been developed and tested to verify the feasibility of the developed method. The test results demonstrated that the system is fast, reliable, and satisfies the precision requirements of the robot.

In order to speed up processing time and increase robustness of the system, active vision techniques have been incorporated in the system. The feature points are located by a search technique where only a small part of the image is used to determine the next search position. This reduces the total number of processed pixels and provides shift-invariant pattern recognition.

The behaviour of the image processing system is defined by the training set provided to the neural network. This makes it very easy to use the system for other image processing tasks. All that is needed to process other images is a new training set. The prototype system was implemented on a standard PC under MS-Windows 3.1. It is thus possible to apply the method to a wide range of image processing tasks.

2.4.3 Handwritten optical character recognition (OCR)

(C. Liisberg)

In early 1992 NIST (National Institute of Standards and Technologies, USA) suggested a "consensus conference" in order to compare and evaluate different handwritten OCR systems on a similar basis. Participants would, on a distinct timing, receive a training set of handwritten, segmented digits, upper and lower case letters, and one month later a test set. After another two weeks the test results in the form of classification and rejection files should be returned to NIST.

The training set consisted of 226,000 digits, 45,000 upper case letters, and 45,000 lower case letters. The test set consisted of 60,000 digits, 12,000 upper case letters, and 12,000 lower case letters. The material was delivered on CD-ROMs. There were 26 participants of whom some delivered more than one system so a total of 44 systems participated.

Risø participated with one system based on a new type of neural networks, the so-called LUT network. Our classification methodology is based on an ensemble of LUT networks, each LUT network being a "neural network"-like approach.

The results of the participants' efforts were displayed at a "Consensus Conference", the NIST COCR held 25-27 May 1992 in Washington D.C., Maryland, USA. Our approach was the best of eight that tried to work from "raw" pixel data, but only number 27 of 44 in the total contest.

The most important experience regarding machine reading of isolated handwritten characters was the following:

- Humans are still better than the best systems: 2.5% errors for a human, 3.6% for the best machine system. More than 70% of the errors made by a majority of systems can be recognised by a human.

- Humans reach almost 0% error at 3% reject. This is a much steeper falloff than that of machine systems.

Further details can be found in the conference proceedings.

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2.4.4 Optical flows

(A. Skov Jensen)

Optical flows are here defined as a series (spatial or temporal) of two-dimensional images. The human eye has a unique capability of perceiving this kind of information, both the absolute information in each image and the differential change between images. The total visual information received by a human (or other biological species) is limited but can be shared between differential and absolute information. For instance, poor resolution of TV images is compensated by the moving images, and a car driver does probably mostly act on differential information. The differential information content in images may be colour changes or changes in local structures, i.e. shifts and rotations. An interesting problem is here whether it is possible to reconstruct earlier images on the basis of a present image and a series of differential images from the past.

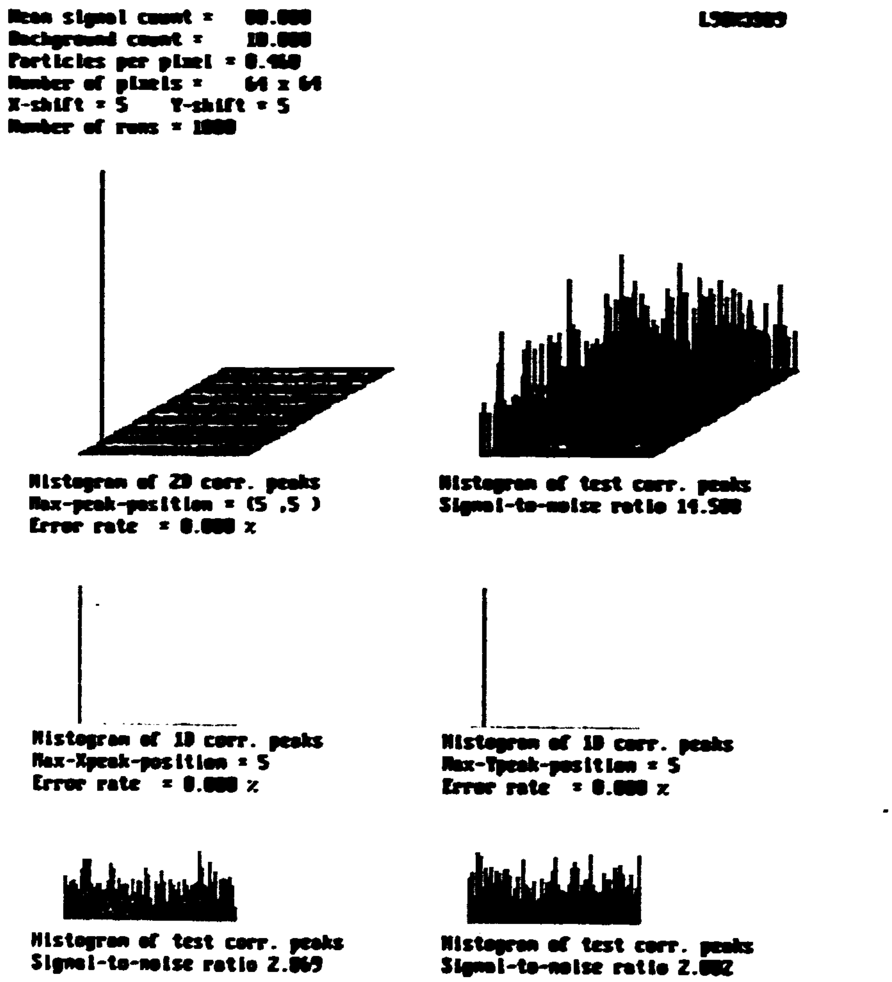

Figure 1. Results from a simulation of a PIV processor. Each histogram represents 1000 correlations of random particle pattern.

A special type of optical flows is moving particle patterns. By looking at two images, separate in time, the velocity flow of the particle can be detected by making local correlations. This technique – particle imaging velocimetry (PIV) – is very demanding from a processing point of view. The reported processing time of a PIV image goes from days to weeks. In the work reported here the aims have been to study efficient recording and data processing methods for the PIV technique with the purpose of constructing instruments capable of "real time" processing of PIV images. Images can be recorded by CCD cameras under low illumination conditions and can be processed with various types of correlators. The statistics of the correlation process have been studied in a series of simulations. An example of this is shown in Fig. 1. A histogram of the correlation results from 1000 simulated experiments is shown, both for a 2D correlation pattern and for 1D projections of the particle images. Both the position and the detected intensity of particles are the random distributed.

2.4.5 FFT processor

(A. Skov Jensen, E. Rasmussen, J. Bundgaard*, and K. M. Enevoldsen* (*Engineering and Computer Department))

A Fast Fourier Transform (FFT) card for a PC with an EISA bus has been designed and constructed in a cooperation between the Optics Section and the Engineering and Computer Department. The FFT processor is supposed to be useful in various research areas: signal processing of temporal bursts, general image processing, 1D and 2D correlations, 3D image processing, and particle imaging velocimetry (PIV). The present layout of the FFT card reflects all these applications though it has not been fully optimised in some cases.

The main features of the card are:

- 1024 points complex FFT in 180 μsec.
- Read-in and read-out time from the PC memory 124 μsec.
- Time of complex multiplication 482 μsec.
- Programmability.
- Several FFT cards can be pipelined or used in parallel.
- Temporal signal can be read in directly from an ADC.

The hardware will be finished in 1992 and tested on the PC in the beginning of 1993.

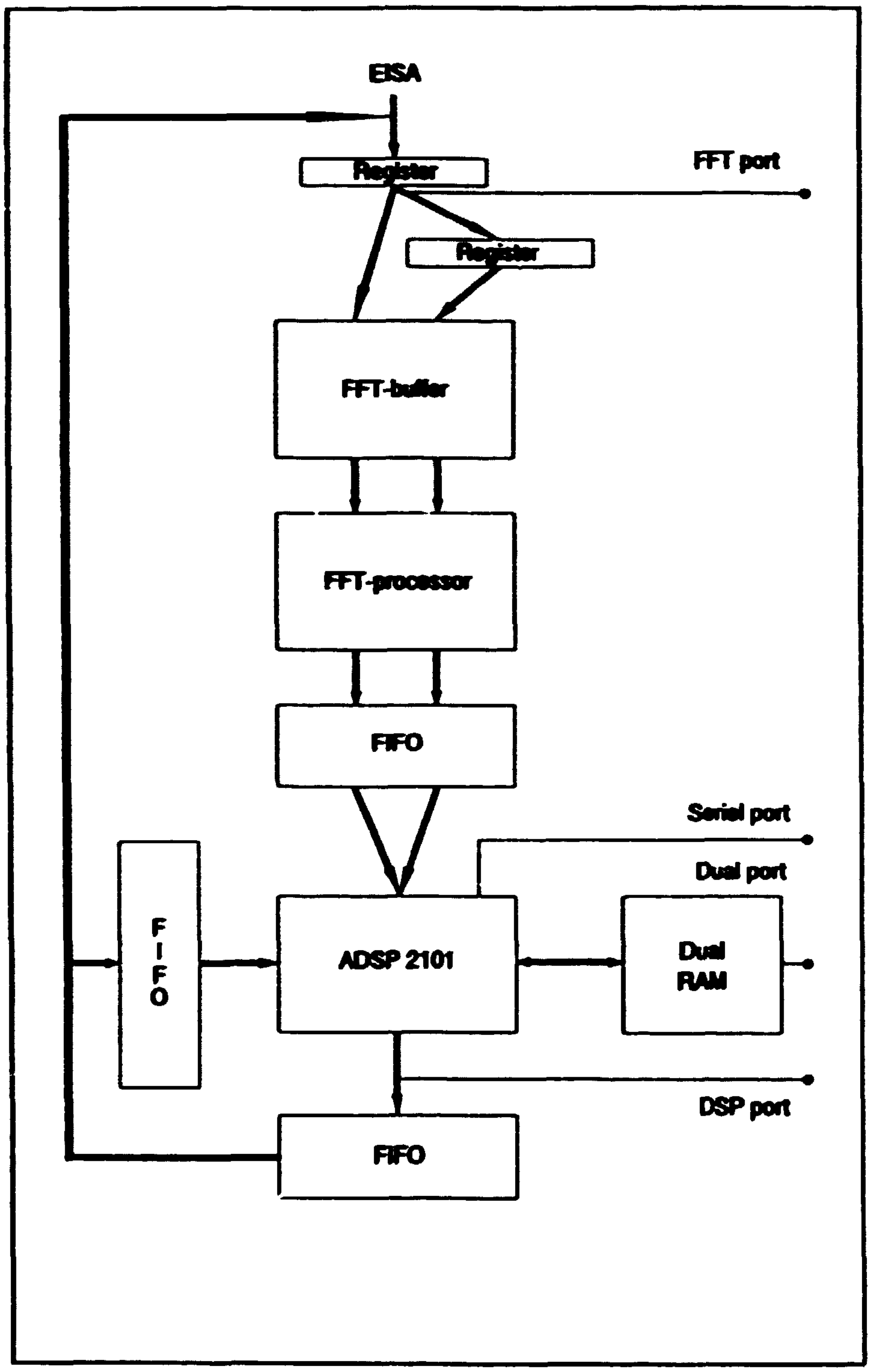

Figure 1. Block diagram of FFT processor card.

2.5 Participants in the Work in Optics

Scientific staff

Christensen, Steen Sloth
Hanson, Steen Grüner
Jensen, Arne Skov
Johansen, Per Michael (from 1 August)
Jørgensen, Thomas Martini (from 1 March)
Lading, Lars
Liisberg, Christian
Lindvold, Lars R. (from 1 April)
Ramanujam, P.S.

Ph.D. students

Elk, Morten (1 April - 30 September)
Jørgensen, Thomas Martini
Lindvold, Lars R. (working at Dantec Measurement Technology)
Kristensen, Jesper Glückstad

Technical staff

Eilertsen, Erik
Hansen, Bengt Hurup
Kristensen, Kim (until 30 June)
Lading, Thomas (1 June - 31 July)
Marcussen, Torben (1 June - 31 July)
Nielsen, Henrik Olskjær (from 22 June)
Rasmussen, Erling
Søegaard, Brian (from 29 June)
Weimar, Bjørn (until 30 April)

Secretaries

Astradsson, Lone
Skaarup, Bitten
Toubro, Lene

Guest scientists

Edwards, Robert V., Case Western Reserve University, Cleveland, USA

Short-time visitors

Brown, R.G.W., Sharp Laboratories of Europe Ltd., Oxford, UK
Psaltis, Demetri, Caltech, Pasadena, USA

Degrees

Jørgensen, Thomas Martini (Ph.D.)
Lindvold, Lars R. (Ph.D.)

2.6 Publications and Educational Activities

2.6.1 Publications

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In addition to the contributions mentioned above a number of reports have been prepared in connection with specific projects.

3 Continuum Physics

3.1 Introduction

In 1992 the Continuum Physics Section was formed based on the former Plasma Physics Section. The change in name reflects a broadening of the research area to include studies of fundamental problems in fluid dynamics and aerodynamics as a natural extension of the basic research in plasma physics which has been carried out since Risø's start in 1957. The research in fusion related plasma problems is continued, but in 1993 this research will be concentrated on theoretical and numerical studies while the fundamental plasma experiments in Risøs Q-machine will be concluded.

In 1992 the scientific programme included the following topics:

- *Nonlinear dynamics of continuum systems*
  This area includes most of the scientific research in the section. The emphasis of the investigations has been on studies of coherent structures in two-dimensional flows. The nonlinear dynamical evolution of these structures, which can be characterised as localised and long-lived vortices, was studied by a combination of theoretical, numerical, and experimental investigations. A detailed understanding of the physical properties of two-dimensional coherent structures is of great importance for the description of plasma confinement in magnetic fusion experiments as well as for many fundamental problems in aerodynamics and fluid dynamics.

- *Fusion plasma physics*
  This topic includes fusion relevant research which has not already been mentioned under the previous heading. The main part of this research was carried out through participation in the scientific work at the joint European fusion experiment JET (Joint European Torus) in England.

- *Pellet injectors*
  Technically advanced pellet injectors are constructed on a contract basis for European fusion laboratories.

3.2 Nonlinear Dynamics of Continuum Systems

3.2.1 Vortex dynamics in two-dimensional flows

(J. S. Hesthaven, J. P. Lynov, J. Juul Rasmussen, and G. G. Sutyrin (P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow 117218, Russia))

A fundamental property of two-dimensional flows is the capability of supporting the existence of long-lived, isolated vortical structures. Vortices in the form of monopoles as well as dipoles and tripoles are often encountered, e.g. in the atmosphere and oceans of large planets as well as in laboratory experiments. Such propagating structures may trap particles and convect them over distances much larger than their scale size. An understanding of their dynamic behaviour is therefore of great importance for describing transport mechanisms.

The monopolar vortex is stationary in isotropic flows. The dipolar vortex may propagate in any direction depending on the relative strength of the two vortices, while tripolar vortices are observed to be nonpropagating, but rotating around the centre of mass of the structure. For anisotropic two-dimensional flows - i.e. on a rotating planet, where the anisotropy is brought about by the variation of the Coriolis parameter with latitude (the 'β-effect') - monopolar vortices are non-stationary and couple to nonlinear, zonally propagating Rossby waves. Strong monopolar vortices may, however, survive for many turnaround times, and will propagate at an angle to the gradient of the Coriolis parameter. Dipoles of permanent form exist only when propagating perpendicular to the gradient of the Coriolis parameter, i.e. zonally.

We have performed a detailed numerical study of the longtime evolution of monopolar and dipolar vortices[1,2,3] in the equivalent barotropic vorticity equation

$$\frac{\partial \phi - \nabla^2 \phi}{\partial t} + \beta \frac{\partial \phi}{\partial x} + [\phi, \nabla^2 \phi] = 0$$

which can be used to model the evolution of two-dimensional flows in the mid-latitudes of large rotating planets. Here ϕ signifies the stream function and β is proportional to the variation of the Coriolis force. A similar equation, the Hasegawa-Mima equation, describes the nonlinear evolution of drift waves in a magnetically confined, low-pressure plasma, where the density gradient causes the anisotropy.

We have used a spectral method in double periodic geometry with an explicit third-order Adam-Bashforth Predictor-Corrector time integration scheme and zero-padding for dealiasing. The simulations were done on an Amdahl VP 1100.

The initial behaviour of strong monopoles is well described by a theory of the development of the first azimuthal mode. In the longtime limit the monopole is observed to propagate north-westward (for a cyclone) and reorganise into a rotating tripole (see Fig. 1), due to an instability, excited by the β-effect, of azimuthal mode number two.

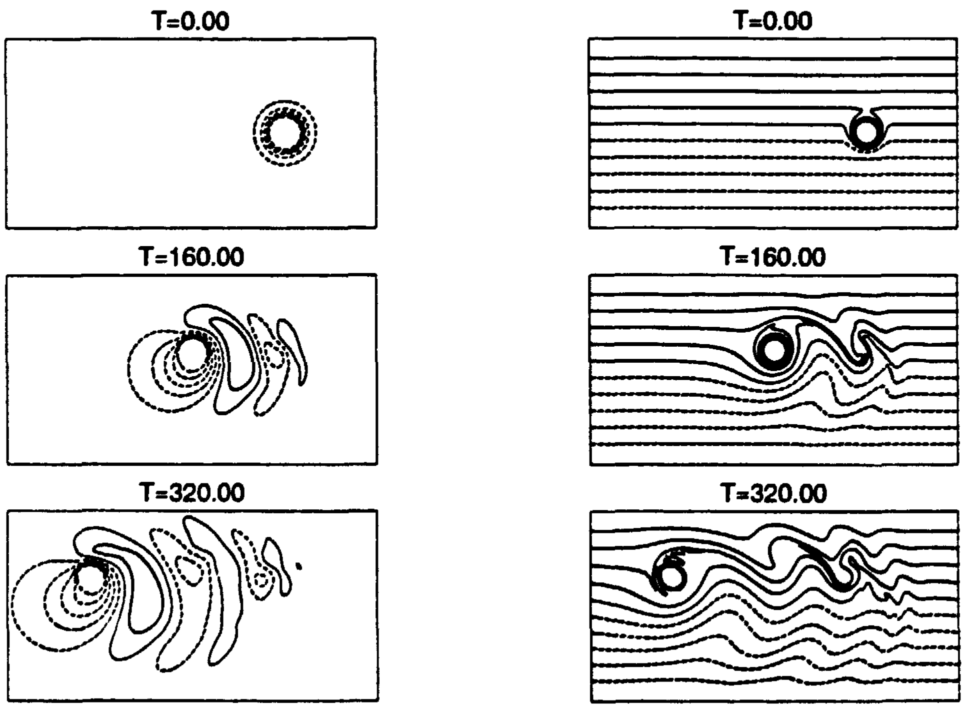

Figure 1. Contour plots showing the temporal development of the stream function (left) and the potential vorticity (right) for a strong vortex. Note the appearance of the reorganised tripolar structure at $T = 320$.

Dipoles started at an angle with the zonal direction may either disintegrate or oscillate around the zonal direction with decreasing oscillation amplitude. Thus, we have found that only strong monopoles provide an efficient transport in the direction of the gradient of the Coriolis parameter (the meridional direction).

In order to study the transport properties of these long-lived coherent structures we have calculated trajectories of massless particles initially released inside as well as outside the initial structure (Fig. 2). These studies clearly illustrate the transporting mechanism of the structures and the capability of trapping particles during the drift. They also show that the physics of the transport mechanism are clearly not diffussion dominated.

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3) Hesthaven, J. S., Lynov, J. P., Rasmussen, J. Juul, and Sutyrin, G. G. (1992). 'Dynamical Properties of Vortical Structures on the Beta-Plane', submitted to Journal of Fluid Mechanics.

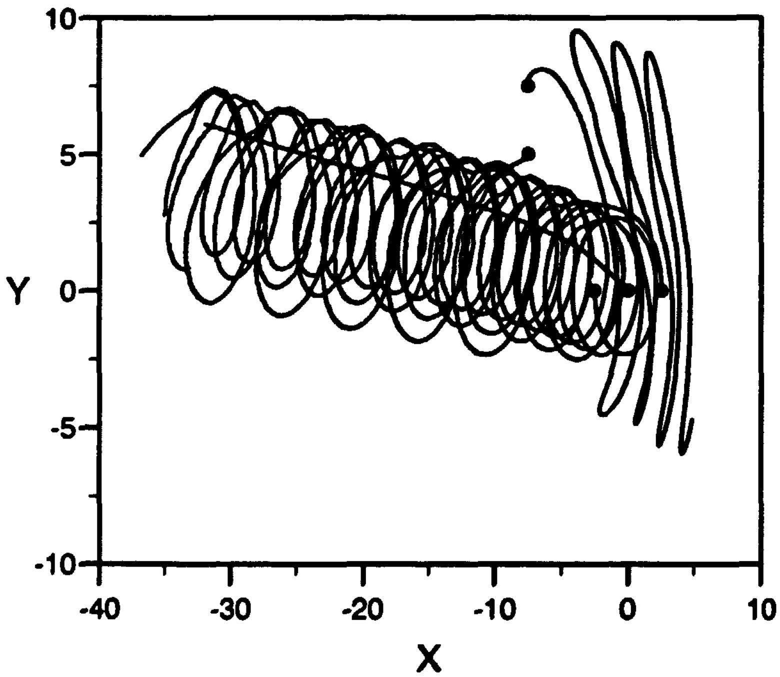

Figure 2. Particle trajectories for particles initially released around a strong vortex. The dots indicate the initial positions.

3.2.2 Numerical simulations of an annular jet

(E. A. Coutsias (University of New Mexico, U.S.A.), J. P. Lynov, A. H. Nielsen, H. L. Pécseli (University of Oslo, Norway), and J. Juul Rasmussen)

In Q-machine experiments on the Kelvin-Helmholtz instability[1] the formation of coherent vortical structures is observed. A numerical model of this instability is based on the flute-mode equations for low-frequency electrostatic fluctuations in strongly magnetised plasmas, i.e. the frequencies are much smaller than the ion cyclotron frequency. These equations are equivalent to the Navier-Stokes equations for two-dimensional incompressible flows:

$$\partial_t \omega + (\hat{z} \times \nabla\phi) \cdot \nabla\omega = \nu\nabla^2\omega,$$

where the normalised potential, ϕ, takes the role of the stream function with the velocity given as $\mathbf{V} = \hat{z} \times \nabla\phi$, $\hat{z}$ is the unit vector in the direction of $\mathbf{B_0}$, and the vorticity, $\omega = \nabla^2\phi$, is equivalent to the charge density. The equation is solved numerically in an annular geometry employing a fully dealiased, spectral scheme[2]. The viscosity on the right-hand side is introduced to suppress, in a controlled manner, the short wavelength ringing that is otherwise produced due to the finite spatial resolution. This term may be thought of as representing damping by gyroviscosity. As initial condition we have set up a vorticity (charge) distribution corresponding to the averaged distribution in the experiments. This distribution corresponds to an azimuthal velocity with a jet-like radial profile, and a radial potential profile increasing from the inner boundary. The potential was kept at a constant, prescribed value on the boundaries, i.e. the radial velocity component vanished on the boundaries. The vorticity was set equal to zero on the boundaries.

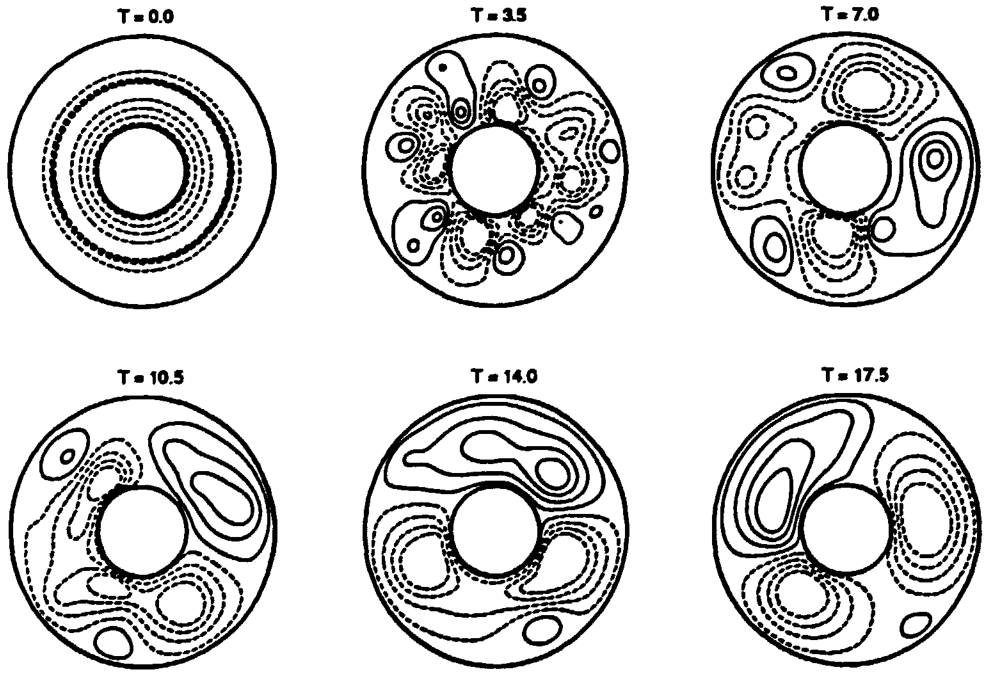

Figure 1. Space-time evolution of the perturbed potential, ϕ, for an initially unstable potential profile. The equilibrium or vacuum profile $\phi_0 \sim \ln r$ has been subtracted. Positive ϕ-values are shown with full lines, negative ϕ-values with dashed lines.

In Fig. 1 we show an example of the evolution of the potential. The flow quickly develops a growing short wave instability in correspondence with predictions from linear stability analysis. However, this high mode number instability evolves nonlinearly, demonstrating the inverse cascade, i.e. coalescence of like-signed vortices, and the instability saturates when the energy is condensed in large-scale structures. Note that for the present profile the $m = 1$ mode is *linearly* stable, while the $m = 2$ mode is only weakly unstable. Thus, the saturated state is far from what would have been predicted by a quasi-linear analysis. This behaviour agrees qualitatively with our experimental observations.

1) Nielsen, A. H., Pécseli, H. L., and Rasmussen, J. Juul (1992). Ann. Geophysicae **10**, 655-667.

2) Coutsias, E. A., Hansen, F. R., Huld, T., Knorr, G., and Lynov, J. P. (1989). Physica Scripta **40**, 270.

3.2.3 Numerical simulations of dipoles colliding with curved walls

(E. A. Coutsias (University of New Mexico, U.S.A.), J. P. Lynov, and A. H. Nielsen)

The dynamics of dipoles colliding with curved walls are studied numerically in an annulus geometry employing a fully dealiased, spectral scheme based on Fourier-Chebyshev expansions. These allow very high resolution of boundary layers. The flow field is described by the two dimensional Navier-Stokes equation

$$\partial_t \omega + (\hat{z} \times \nabla\psi) \cdot \nabla\omega = \nu \nabla^2 \omega,$$

where ψ is the stream function with the velocity given as $\mathbf{v} = \hat{z} \times \nabla\psi$, $\omega = \nabla^2\psi$ is the vorticity, and ν is the viscosity. The flow is subject to no-slip conditions so that it matches the wall velocity at the boundaries. We have implemented various global accuracy checks to diagnose the performance of the scheme: the conservation of total circulation is monitored, while comparisons are performed between the computed and theoretically predicted viscous evolutions for the total energy and total enstrophy (or squared vorticity). All these were found to be in close agreement.

In our numerical studies a Lamb dipole was made to collide with both concave and convex curved walls. Examples of the numerical results are shown in Figs. 1 and 2. We can summarise the main aspects of such interactions as the dipole approaches the wall, it induces opposite-sign wall vorticity layers. These thicken due to viscosity. At minimum approach these wall layers roll tightly into secondary vortices and couple with opposing primary lobes. Wall vorticity production continues, feeding the secondary vortices through vortex sheets, as the former are being advected by the primaries. At a critical instant detachment of the combined structures occurs. These examples compare well with experimental observations in a rotating water tank, described in section 1.2.15.

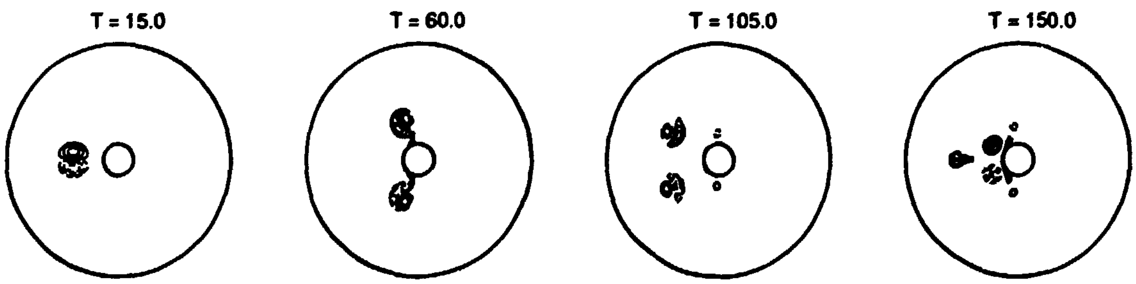

Figure 1. Numerical results showing contour plots of the vorticity field for a dipole with initial Reynold number $Re = 2400$ interacting with a convex wall. Dashed lines indicate negative values.

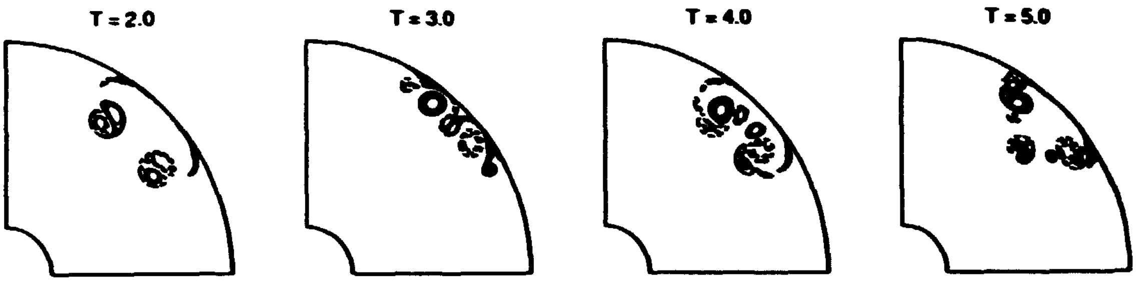

Figure 2. Same as Fig. 1 for a dipole with $Re = 4000$ interacting with a concave wall. At $T = 2$ the rebounded dipoles are already formed.

3.2.4 Numerical investigations of wall-bound vortical structures

(E. A. Coutsias (University of New Mexico, U.S.A.) and J. P. Lynov)

Incompressible, inviscid two-dimensional flows away from boundaries possess special stationary solutions in the form of coherent, isolated vortical structures. These solutions can be classified in terms of the spatial moments of the vorticity distribution about their centres. In real flows one must always deal with boundaries, and although the vorticity field can initially be confined away from walls, momentum carrying structures such as dipoles will eventually approach walls and interact strongly with them.

A generic outcome of our numerical studies based on an accurate spectral method[1)] is the apparent evolution of an initially complex interaction process into a simpler configuration in which most of the remaining vorticity is concentrated near the wall, seemingly trapped in what can be called 'surface states'. These appear to be long-lived, robust structures in which the original vortex couple is separated by halos of oppositely signed, wall generated vorticity. For the time intervals investigated up till now, of order 3-4 rebound times, the halos still contain several small vortices rotating about the primaries which are only slowly evolving. These surface states can act as enstrophy sources, pumping wall vorticity away from the wall.

Another class of wall-bound structures appears to play an important role in the process of vortex rebound. Clearly, a structure compatible with a line of zero velocity could coexist with a rigid boundary and produce no strong boundary layers. As good candidates that fulfil this property approximately we consider dipoles with special vorticity balance to create a velocity field with a stagnation point on the perimeter. A special dipole in this class is the 'rolling dipole' which rotates about a point on its perimeter, and has zero velocity on the antipodal point. For this dipole the ratio of circulations in the positive and negative part is 2.65 and we believe it constitutes a fair approximation for the secondary dipoles emerging from dipole-wall collisions at moderate Reynolds numbers.

1) Coutsias, E. A. and Lynov, J. P. (1991). Physica D 51, 482-497.

3.2.5 A nonlinear dipole vortex solution to the Euler equations

(J. S. Hesthaven, J. P. Lynov, P. Michelsen, A. H. Nielsen, J. Juul Rasmussen, M.R. Schmidt (University of Odense, Denmark), E. G. Shapiro*, and S. K. Turitsyn* (*Institute of Automation and Electrometry, Novosibirsk, Russia)

Stationary solutions to the Euler equations describing two-dimensional flows have a functional relationship between the vorticity, ω, and the stream function, ψ, i.e. $\omega = f(\psi)$, (ω and ψ are related by $\omega = -\nabla^2\psi$). For a particular nonlinear form of f, $f(\psi) = -\psi + \psi^3$, a localised solution with a dipolar vortex structure has been found. This solution is characterised by having two cores of opposite vorticity each of which is shielded by a region with vorticity of opposite sign and the structure is not moving. To investigate the stability of this solution we have solved the Euler equations numerically using a spectral method with the solution as the initial value. In Fig. 1 we show the development of the vorticity field. The nonlinear solution is observed to be unstable. It splits into two dipoles moving in opposite directions: a "strong" dipole composed of the vorticity in the two cores and a "weak" dipole composed of the vorticity initially shielding the two cores. The "strong" dipole is found to be steadily propagating. By performing a scatter plot, i.e. by plotting ω as function of the streak function $\phi = \psi - ux$ (u is the velocity in the y-direction), we have confirmed that this dipole reaches a stationary state with a nonlinear relationship between ω and ϕ. We find that $f(\phi) = -\alpha\phi - \beta\phi^3 + \gamma\phi^5$, where $\alpha, \beta, \gamma > 0$ inside a separatrix of almost circular shape and $f(\phi) = 0$ outside the separatrix. This appears to be a new type of stationary dipole solution to the two-dimensional Euler equations.

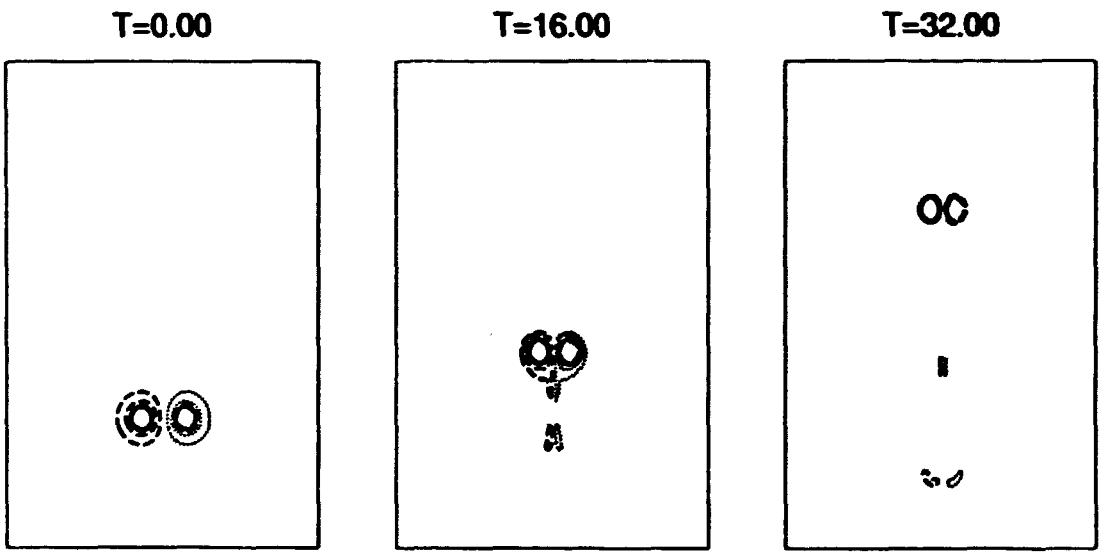

Figure 1. The evolution of the vorticity field of a nonlinear dipole solution. Dashed contour lines indicate negative vorticity while dotted contour lines indicate positive vorticity.

3.2.6 Vortices associated with toroidal ion temperature gradient driven fluctuations

(W. Horton (University of Texas at Austin, USA), D. Jovanovic (Institute of Physics, Belgrade Yugoslavia), and J. Juul Rasmussen)

Coherent vortical structures associated with toroidal ion temperature gradient driven fluctuations in a sheared magnetic field have been analysed. These fluctuations, which are usually called η_i-modes, are thought to be an important mechanism for the anomalous transport of ion thermal energy in tokamak experiments. The present study was motivated by results from high resolution numerical simulations of η_i-turbulence, where coherent vortical structures were observed to develop spontaneously. These structures had a dominating influence on the turbulence, and the associated transport was found to be significantly reduced as compared with predictions from quasi-linear theory. The analysis was based on three coupled nonlinear equations for the evolution of the potential, the parallel ion velocity, and the ion pressure. Two types of vortex structures were found: one type for a weak magnetic shear, which is a generalisation of the usual dipole vortex solution for drift waves, and a second type of solution for strong magnetic shear where the convective nonlinearity in the parallel velocity field generates a cubic trapping nonlinearity in the vorticity equation. This solution is possible as a dipole vortex if the fluctuation amplitude is sufficiently large to produce wave trapping. The existence of these vortex structures shows the possibility of explaining the saturated states observed in the numerical simulations as self-organised nonlinear states which are not associated with wave-like motion. The vortices may trap plasma and carry it over distances that are large compared with their scale size. Thus, they are very effective in providing transport of particles and energy, and this tranport will be inherently different from the diffusion dominated transport associated with wave-like fluctuations.

3.2.7 Sharp criteria for wave collapse

(E. A. Kuznetsov*, J. Juul Rasmussen, K. Rypdal (University of Tromsø, Norway), and S. K. Turitsyn* (*Inst. Automation and Electrometry, Novosibirsk, Russia))

In two and three dimensions it is well known that the cubic Schrödinger equation has collapsing solutions, i.e. the solution develops a singularity in a finite time[1]. For the two-dimensional case, the critical case, a sharp necessary condition for collapse is that the "mass" of the initial wavefield, $\int |u(x, t = 0)|^2 \, dx$, must be larger than or equal to the "mass" of the lowest order stationary ("soliton") solution. For the three-dimensional case, the supercritical case, it has been shown, by applying integral relations, that a sharp sufficient condition for collapse is that the "Hamiltonian", H, corresponding to the initial wavefield must be smaller than H_{sol}. Here $H_{sol} > 0$ is the "Hamiltonian" corresponding to the stationary ("soliton") solution with the same "mass" as the initial wavefield. Note that this "soliton" solution is unstable. It has been conjectured that the above condition is also a necessary condition for collapse. Generally it has been suggested that unstable "soliton" solutions for a class of nonlinear evolution equations could play the role as the boundary between collapsing and noncollapsing solutions[2]. We have examined these criteria for the case of the cubic Schrödinger equation by solving it numerically in radial symmetry. Our results for the two-dimensional case confirm the prediction of a sharp necessary condition. For the three-dimensional case we found that $H < H_{sol}$ is indeed a sharp sufficient criterion for collapse provided that the "mass" is not too small. For small "mass" this condition turns out to be sufficient for noncollapse. On the other hand, the condition is not necessary since for $H > H_{sol}$ we may have both collapse and noncollapse. However, in this region the numerical results indicate that it is possible to have sharp collapse criteria for a restricted class of initial conditions.

1) Rasmussen, J. Juul and Rypdal, K. (1986). Physica Scripta 33, 481.
2) Turitsyn, S. K. Phys. Rev. A, submitted for publication.

3.2.8 On localisation in the discrete nonlinear Schrödinger equation

(O. Bang*, P. L. Christiansen* (*Laboratory for Applied Mathematical Physics, The Technical University of Denmark, Lyngby), and J. Juul Rasmussen))

The one-dimensional discrete nonlinear Schrödinger equation (DNSE) with arbitrary power nonlinearity describes a system of coupled anharmonic oscillators. The dispersive coupling has a strength h^{-2}, where h is the distance between adjacent sites. We have performed a detailed numerical investigation of the localisation or self-trapping in the DNSE, i.e. the dynamic stable state when most of the energy gets concentrated at a single site. There are no analytical results for the evolution of the DNSE in the regime of intermediate number of degrees of freedom $f > 3$. However, in the continuum limit ($f \to \infty$) the DNSE corresponds to a partial differential equation, the nonlinear Schrödinger equation, for which conditions for blowup are well known. In a continuum system blowup, which implies that the solution develops a singularity in finite time, would be the equivalent to localisation in the discrete system. One of the aims of the present work is to examine to what extent the predictions for the nonlinear Schrödinger equation can be applied to the DNSE. Using the ground state solitary wave solution as the initial condition for the numerical solution of the DNSE, we found that localisation in a finite time occurred even for a subcritical nonlinearity (i.e. there would not be blowup in the corresponding nonlinear Schrödinger equation) provided the discretisation was sufficiently coarse (h was sufficiently large). Thus, in this regime the dynamics in the discrete system are markedly different from the dynamics in the continuum system. Increasing the discretisation (decreasing h) we found a critical value of h where there was a sharp transition in the dynamics of the solution which changed from localisation to a smooth oscillatory behaviour with an amplitude that decreased with decreasing h. For a supercritical nonlinearity localisation was always observed as expected from the nonlinear Schrödinger equation. A variational approach has been used to give a qualitative explanation of the dynamics in the discrete system.

3.2.9 Euler-Lagrange transformations in two-dimensional isotropic turbulence

(J. S. Hesthaven, J. P. Lynov, A. H. Nielsen, J. Juul Rasmussen, and H. L. Pécseli, (University of Oslo, Norway))

A central problem in the study of turbulent flows deals with their capability of dispersing particles or other passive contaminants. A statistical analysis of this problem is readily carried out in terms of the Lagrangian correlation function of the fluctuating velocity field, i.e. the one derived from the fluctuating velocity components obtained along the orbit of dispersing particles. Unfortunately, readily obtainable averages and correlations are obtained by Eulerian sampling, i.e. by detecting equipment at rest or following a prescribed orbit, e.g. moving along a straight trajectory at constant speed. The study of turbulent diffusion may be viewed as the problem of deducing the desired Lagrangian statistical properties of the flow from measurements based on Eulerian sampling of the quantities. Since the two methods of sampling are very different, there is no reason to expect a simple correspondence.

We have performed a study[1] of the validity of a theory[2] which analytically derives the Eulerian and Lagrangian autocorrelation functions and states that these may be obtained by measuring the one-dimensional energy spectrum of the flow.

A homogeneous, isotropic turbulent flow has been simulated by a direct numerical simulation using a spectral method in double periodic geometry with an explicit third-order Adam-Bashforth Predictor-Corrector time integration scheme and zero-padding for dealiasing. The particles have been traced using a bicubic spline as interpolation method and a semi-implicit second-order Runge-Kutta time integration scheme. In most simulations we used 256^2 modes and 3025 particles. The simulations were performed on an Amdahl VP 1200.

Our study indicates that the Eulerian correlation function does not agree well with the simulated autocorrelation function whereas there seems to be a good correspondence between the theoretical and the simulated Lagrangian correlation function. It has, however, been confirmed that the Eulerian correlation time scale is larger than the Lagrangian correlation time scale, as predicted by the theory. It has also been shown that by slightly modifying the original theory in order to more properly take into account diffusion limit behaviour, the theory seems to agree remarkably well with the correlation functions obtained by the simulations.

These results suggest that information about the Lagrangian correlation function in homogeneous, isotropic two-dimensional turbulence may indeed be obtained by measuring the Eulerian energy spectrum, which may readily be done.

1) Hesthaven, J. S., Lynov, J. P., Nielsen, A. H., Rasmussen, J. Juul, and Pécseli, H. L. (1992). "Numerical Studies of the Eulerian-Lagrangian Transformations in Two-Dimensional Isotropic Turbulence". In: Proc. of First European Computational Fluid Dynamics Conference, Brussel 1992, Vol 1, p. 223, Elsevier.
2) Wandel C. F. and Kofoed-Hansen, O. (1962) J. Geophys. Res. **67**, 3089.

3.2.10 *Nonlinear modulational instability of whistler waves*

(V. I. Karpman (Izmiran, Moscow, U.S.S.R.), J. P. Lynov, P. Michelsen, and J. Juul Rasmussen)

The nonlinear evolution of the modulational instability of whistler waves propagating along a constant external magnetic field has been investigated numerically. The equations of the modulational instability in which the whistlers are coupled to fast or slow magnetosonic waves have been studied by Karpman and Shagalov[1]. The case with the fast wave has been studied numerically by Karpman et al.[2]. It was found that for long-time evolution the instability proceeded in a quasi-recurrent manner at least for relatively low amplitudes.

We have studied the interaction of whistlers and slow magnetosonic waves. The coupled partial differential equations describing the time evolution of the slowly varying whistler electric field, Ψ, and the slowly varying density, ν, were solved numerically for different parameters within the unstable branch. In no cases did we observe a recurrent behaviour and the energy was constantly spreading to the higher mode numbers. An example of a low amplitude case is shown in the Fig. 1. The initial behaviour agrees well with the one found in Ref. 1. In that phase the modulation grows in accordance with the linear predictions. The modulation has a spatial structure resembling cells stretched along the z-axis (the direction of the magnetic field) with the maximum of $|\Psi|^2$ slightly in front of the maximum of ν and almost no propagation along z. At the termination of the linear growth the phase shift between the maximum of $|\Psi|^2$ and the maximum of ν vanishes. The subsequent oscillations in the maximum of $|\Psi|^2$ seem to be correlated with oscillations in the phase shift between the maximum of $|\Psi|^2$ and the maximum of ν. In this stage the energy is spreading to higher mode numbers with the tendency that the spreading proceeds mainly along the K_z-direction. Accordingly, the cells in the spatial structure of $|\Psi|^2$ tend to shrink in particular along the z-axis. Calculations with higher initial amplitude show a similar evolution with a faster spreading of the energy. We thus expect that the energy ultimately cascades to arbitrary high wave numbers, resulting in a turbulent wave field. To investigate the evolution in more detail the numerical code is now being optimised and transferred to Risø's Convex C220.

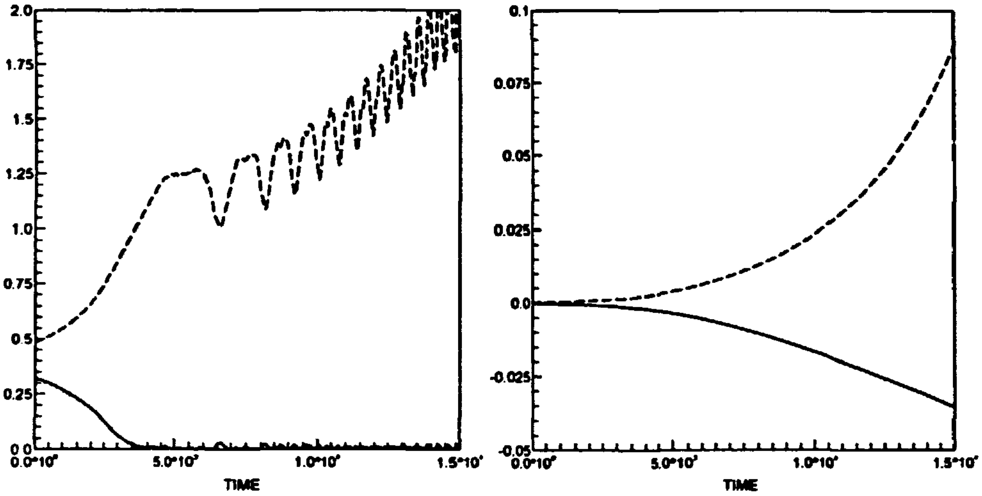

Figure 1. The temporal evolution of the maximum and minimum of $|\Psi|^2$ (left, the vertical scale is in units of 10^{-3}) and of ν (right).

1) Karpman, V. I. and Shagalov, A. G. (1987). J. Plasma Physics **38**, 155.
2) Karpman, V. I., Hansen, F. R., Lynov, J. P., Pécseli, H. L., and Rasmussen, J. Juul (1990). Phys. Rev. Lett. **64**, 890.

3.2.11 Comparison of fast Fourier transform libraries on the Amdahl VP 1200

(J. DuCroz (Numerical Algorithms Group Ltd, Oxford, England), J. S. Hesthaven, and J. Waśniewski (The Danish Computer Center for Research and Education UNI•C, Lyngby, Denmark))

The Fast Fourier Transform (FFT) is used as the basic tool when solving an increasing number of scientific and technological problems, e.g. nonlinear dynamics, artificial intelligence, signal analysis, optics, etc.

We have performed a benchmark study[1)] of two excellent FFT libraries offered at the newly installed Amdahl VP 1200 at UNI•C; the NAG Library, which is a general purpose numerical library, and the Siemens FFT Library, which has recently been installed at the Amdahl VP 1200 vector computer.

The benchmarks clearly indicate that the Siemens FFT Library is generally superior to the NAG Library. This is not surprising since the Siemens FFT Library is designed for taking better account of the very special hardware architecture of the Amdahl VP 1200 than does the NAG Library. However, a new, not yet released, NAG FFT subroutine library shows a significant improvement as compared with the older NAG Mk 13 release, especially when doing FFTs of very long sequences. These subroutines will be in the NAG Mk 16 release, but have very recently been installed at the UNI•C Amdahl VP 1200.

We have observed performance for the Siemens FFT Library of up to 413 MFlops (72% of peak performance) for Complex-to-Complex FFTs and 350 MFlops (61% of peak performance) for Real-to-Hermitian and Hermitian-to-Real FFTs.

The study clearly indicates that using the Siemens FFT Library will be an advantage for a large majority of users who are dependent on the performance of the FFT when addressing their problems.

1) DuCroz, J., Hesthaven, J. S., and Waśniewski, J. (1992). "Comparison of Two FFT Libraries on the Amdahl/Fujitsu VP Computer - NAG and Siemens Libraries", Supercomputer 51, XI-5, pp. 31-37.

3.2.12 Visualisation of numerical flow calculations

(L. Bækmark, J. P. Lynov, and P. Michelsen)

Numerical flow calculations often require a vast amount of computer time. It is therefore of the utmost importance to obtain a maximum of information from the results by utilising advanced visualisation techniques. The word visualisation covers fields like computer graphics, animation, image processing, etc. The numerical results from the flow calculations, normally obtained on a supercomputer, consist of files of three-dimensional arrays, with two spatial dimensions and one dimension giving the time sequence. A visualisation program, FRAME, has been developed with the following purposes: (a) to perform certain transformations on the input data, (b) to present the data on screen or on a hardcopy device as a time series of two-dimensional plots and, (c) to produce new data files which can be used as input to video animation or for immediate animation on screen.

The numerical results from flow calculations based on spectral methods may be results describing the real physical variables (velocity, vorticity, etc.), or it can be the Fourier modes of the physical variables. The latter may in general be expressed satisfactorily with a smaller amount of data. By including inverse fast Fourier transforms and other transformations normally used in the flow calculation programs in the visualisation program, data transmission time and disk space usage can be greatly reduced.

The FRAME program can show plots of different types (contour, surface, etc.) for different times and for different transformations in any position of a window consisting of a number of columns and a number of rows of individual frames.

In order to produce video animation, Targa files can be generated from the visualisation program when the various plot parameters have been established. These files are subsequently transferred to a fast pc, which can be used for control of a super-VHS video editing recorder. In 1992 this system has been extended with a video editor and another video player to give more features needed for detailed animated visualisation.

3.2.13 Dynamics of dipolar vortices on a "topographic beta-plane"

(J. Juul Rasmussen, M. Nielsen, and B. Stenum)

Dipole vortices seem to be one of the universal outcomes of any forcing in two-dimensional flows. Thus, they are of great importance for the dynamic evolution of the flow. In an isotropic flow dipoles may propagate steadily in any direction, but on the β-plane, where anisotropy is brought about by a spatial variation of the Coriolis force (the β-effect), dipole vortices are only steadily propagating when they move in the zonal direction, i.e. perpendicular to the gradient in the Coriolis force. This corresponds to the east or west direction on a rotating planet. When dipoles are launched with some angle, α, to the west-east direction (α = 0 for eastward propagation), they will either end up propagating eastward after a damped oscillatory motion, or they will disintegrate if the angle is larger than some critical value, depending on their velocity[1].

We have performed an experimental investigation of the dynamics of dipoles on the β-plane in a rotating water tank. The square tank has a side length of 1 m and the depth of the water was D = 15 cm. The rotation rate of the tank was $\Omega = 0.63$ rad s^{-1} and the upper surface of the water was free. To model the β-effect an inclined plate with a constant slope, s, was placed at the bottom of the tank. The ambient potential vorticity of this "topographic β-plane"[2] is given as $\beta y = (2s\Omega/D)y$. The direction up the slope (y-direction) corresponds to the north direction. Dipole vortices were excited by a short jet of dyed water. By deflecting the jet, almost symmetrical dipoles could be excited and their direction of propagation could be controlled. The velocity and size of the dipoles were also controllable within a rather broad range by changing the duration of the jet and the pressure.

The main results of our investigations are in qualitative agreement with the results from the recent numerical simulation[1] described above. In particular, we have investigated the criteria for the disintegration of the dipoles and find that the critical angle, α_c, above which the dipole disintegrates, increases with increasing dipole velocity relative to β. For the disintegrating dipoles the two poles were observed to separate. The cyclonic vortex propagated in the north-west direction while the anticyclonic vortex tended to propagate in the south-west direction in agreement with the behaviour of monopolar vortices on the β-plane[2].

1) Hesthaven, J. S., Lynov, J. P., and Nycander, J. (1993). Phys. Fluids. A5, March, in press.
2) Carnevale, G. F., Kloosterziel, R. C., and van Heijst, G. J. F. (1991). J. Fluid Mech. 233, 119.

3.2.14 Damping of a vortex ring in a stratified fluid

(B. Stenum, S. B. Dalziel*, and P. F. Linden* (*DAMTP, University of Cambridge, England))

Coherent structures appear in two-dimensional (2D) as well as three-dimensional (3D) flows. In particular, the formation of coherent vortex structures is likely in 2D flows as a result of self-organisation during the inverse energy cascade characterising these flows.

In stratified fluids (e.g. fluids with a nonzero density gradient in the vertical direction) the vertical motion is suppressed by the stratification, forcing the flows to being two-dimensional. Subsequently 2D, coherent vortex structures are formed. During the damping of the vertical motion internal waves are generated by means of which energy is radiated away from the initial flow. The formation of dipole structures in 2D system as, e.g., stratified and rotating fluids is well known from studies of a turbulent jet injected into the system[1].

Preliminary studies on the transition from an elementary 3D vortex structure to a dipole in 2D systems have been undertaken in collaboration with Department of Applied Mathematics and Theoretical Physics (DAMTP), University of Cambridge. In the studies a vortex ring produced by injection of a water puff[2] was emitted horizontally into a stratified fluid. Gradually, the vertical motion in the ring is damped due to energy loss to internal waves and to a smaller degree to mixing and viscosity. After propagating some distance depending on the initial energy of the vortex ring and the strength of stratification the vortex ring collapses into a horizontal motion and, subsequently, a plane dipole is formed. This dipole continues to propagate horizontally at a velocity much less than that of the initial vortex ring.

The transition of a vortex ring to a dipole has not been quantified previously.

1) van Heijst G. J. F. and Flor, J.B. (1989). Nature **340**, no. 6230, 212.
2) Glezer, A. (1988). Phys Fluids **31**, 3532.

3.2.15 Experimental studies of dipoles colliding with curved walls

(M. Nielsen, J. Juul Rasmussen, and B. Stenum)

It is well known that momentum transfer to a two-dimensional system as a rotating fluid often results in the formation of stable, isolated vortex dipoles[1]. The stability of such dipoles in collisions with walls of different shape ranging from thin cylindrical obstacles to convex curved walls has been studied in the rotating tank setup.

The setup consists of a turntable rotated with an angular frequency of 0.63 Hz. Onto this table a water filled (15 cm) square tank with side walls of length 1 m and flat bottom is placed. In the tank various wall structures can be placed. The dipoles are produced by injection of well-defined, dyed jets. Typically, asymmetric dipoles with a diameter of about 20 cm and a propagation speed of about 1 cm/s are formed. However, by modifying the shape of the inlet jet by a plate placed in front of the nozzles almost symmetrical dipoles can be produced. The tank is surveyed by a video camera following the rotating system and coupled to a videotape recorder and a monitor via a set of slip rings.

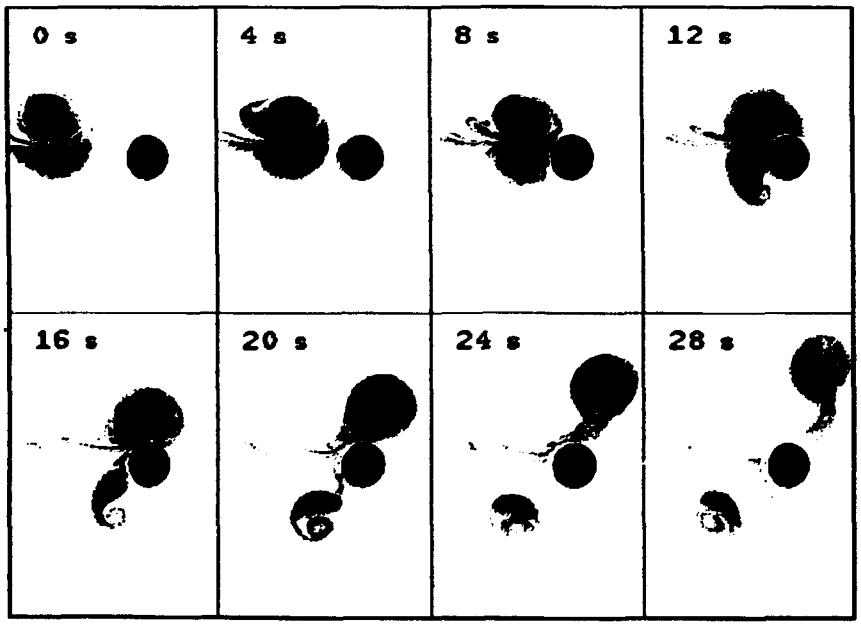

Figure 1. Dipole colliding with an obstacle.

In off-axis collisions with thin obstacles (0.5 cm) the dipoles were found to reconstruct after the interactions. However, in collisions close to the axis the dipoles seem to split into two separated dipoles. At larger thicknesses of the obstacle the dipoles split into two dipoles for off-axis collisions as well (see Fig. 1). This splitting into two dipoles is a result of opposite-signed vorticity created at the walls during the collision and subsequent formation of new partners for the poles in the initial dipole. However, the new partners are weaker than the original poles resulting in circular trajectories of the new dipoles. In that way exact axial collisions of symmetrical dipoles seem to result in collision and partner exchange between the dipoles formed in the interaction with the thick obstacle thus forming a new dipole entirely consisting of wall vorticity.

For collisions with flat and convex curved walls the general picture is similar, but the different shapes of the walls result in different emission angles of the new dipoles. For a flat wall the rebounding dipoles were found to circle around to perform new collisions with the wall leaving the weak partners inactive together close to the wall. For the collisions with convex curved walls the angle of emission of the rebounding dipoles leads to collisions away from the wall resulting in the formation of a new dipole formed of wall vorticity. The studies are in quantitative agreement with numerical studies described in section 1.2.3.

1) Kloosterziel, R. C. and van Heijst, G. J. F (1991). J. Fluid Mech. **223**, 1.

3.2.16 Velocity field measurements by means of particle tracking

(J. Juul Rasmussen and B. Stenum)

Coherent structures play an important role in the dynamics of atmospheric and oceanic flows as well as in laboratory experiments on two-dimensional systems. It is therefore important to be able to measure whole velocity fields instantaneously.

In order to measure two-dimensional velocity fields in our laboratory experiments we have installed a setup based on particle image velocimetry at particle densities sufficiently small to allow tracking of the individual particles[1)]. Small particles are added to the fluid, illuminated by a sheet of light, and the experiment is recorded on a videotape recorder. In the subsequent image processing and analysis the video frames are digitized one by one, the particles are localised and matched to one another from one frame to the next. In this way the particle tracks and hence, e.g., the velocity field and its evolution can be determined. Particle tracking velocimetry which has its roots in flow visualisation by means of particle streak photography is a simple but efficient tool for measurements of velocity fields compared with particle image velocimetry at high particle densities[2)].

The system has been applied for the dipole wall interactions and, in particular, for the preliminary studies on the transition of a vortex ring to a dipole in a stratified fluid. Figure 1 shows the velocity field in the vertical plane of a vortex ring in a homogeneous fluid.

The system for particle tracking has been developed at Department of Applied Mathematics and Theoretical Physics, University of Cambridge, England, and the software package, DigImage, is commercialised through Cambridge Environmental Research Consultants Ltd. The software supports a personal computer, a commercial Super VHS videotape recorder (Panasonic, model AG-7350) and frame grabber (Data Translation, model 2862) with a resolution of 512×512 pixels at 256 grey levels. The system was financially supported by a grant from the Danish Natural Science Research Council.

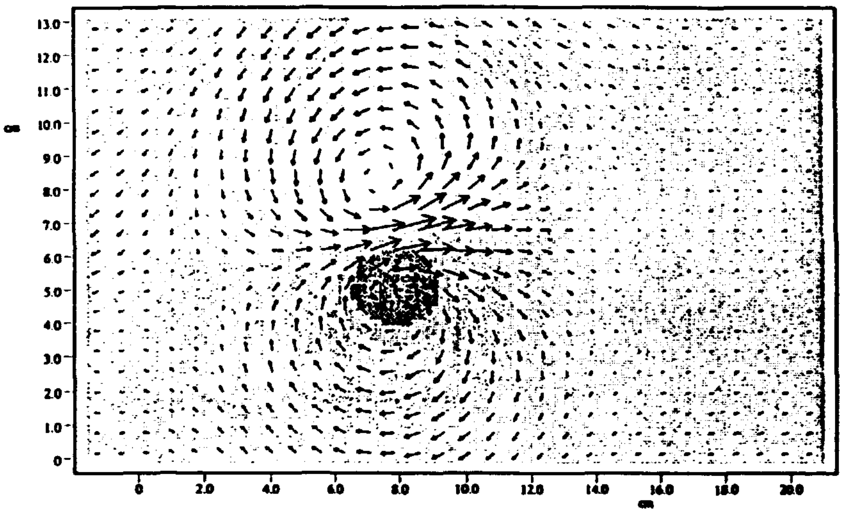

Figure 1. Velocity field in the vertical plane of a vortex ring in a homogeneous fluid.

1) Dalziel, S. B. (1992). Applied Scientific Research **49**, 217.
2) Adrian, R. J. (1991). Annu. Rev. Fluid Mech. **23**, 261.

3.2.17 Cross-field transport caused by two-dimensional plasma turbulence

(A. H. Nielsen, H. L. Pécseli, and J. Juul Rasmussen)

The experimental studies of low frequency, flute-type plasma turbulence have been continued. The investigations are performed in the Q-machine plasma. Fluctuations are generated by the Kelvin-Helmholtz instability due to a strongly sheared azimuthal flow of the residual plasma surrounding the main plasma column. The radial potential variation in the residual plasma and thereby the azimuthal flow can be controlled by the bias of a limiting aperture inserted perpendicular to the plasma column. We have performed a detailed analysis of the anomalous plasma transport associated with the turbulence. This is done by analysing the radial component of the fluctuating flux $\Gamma = nE/B_0$, where n is the density fluctuations and E is the azimuthal component of the fluctuating electric field. The averaged value of Γ, Γ_0, gives the part of the plasma transport out of the plasma column which can be attributed to the turbulent fluctuations. The radial dependence of Γ_0 as well as that of the fluctuation levels of both E and n have been measured simultaneously fo' varying conditions. We found that Γ_0 had the maximum value at a radial position just outside the main plasma column. For larger radii Γ_0 decreased monotonically almost as $1/r$, where r denotes the radial position. However, the absolute magnitude of Γ_0 did not appear to be correlated with the absolute fluctuation level and the position of maximun of Γ_0 was usually not coinciding with the position of the maximum fluctuation level, as would be expected from considerations based on quasi-linear theory. These findings are consistent with our previous observation that the evolution of the turbulence is dominated by coherent structures[1]. To investigate the transport further we have obtained the complex cross-power spectrum $S(f) = |S(f)|\exp(\psi(f))$ by Fourier transforming the cross-correlation of n and E. An example of the cross-power spectrum is shown in Fig. 1. The phase spectrum indicates the phase difference between n and E at the given frequency, while the amplitude spectrum is a measure of the "energy" content in the given frequency component. By noting that the averaged flux is given by

$$\Gamma_0 = \int |S(f)| \cos(\psi(f)) df$$

we observe that modes with $\psi(f) = \pi/2 + j\pi, j = 1,2,3..$ do not contribute to the transport, even if they may have high amplitudes. Thus, from Fig. 1 we see that it is mainly the low frequency modes that are effective in the transport.

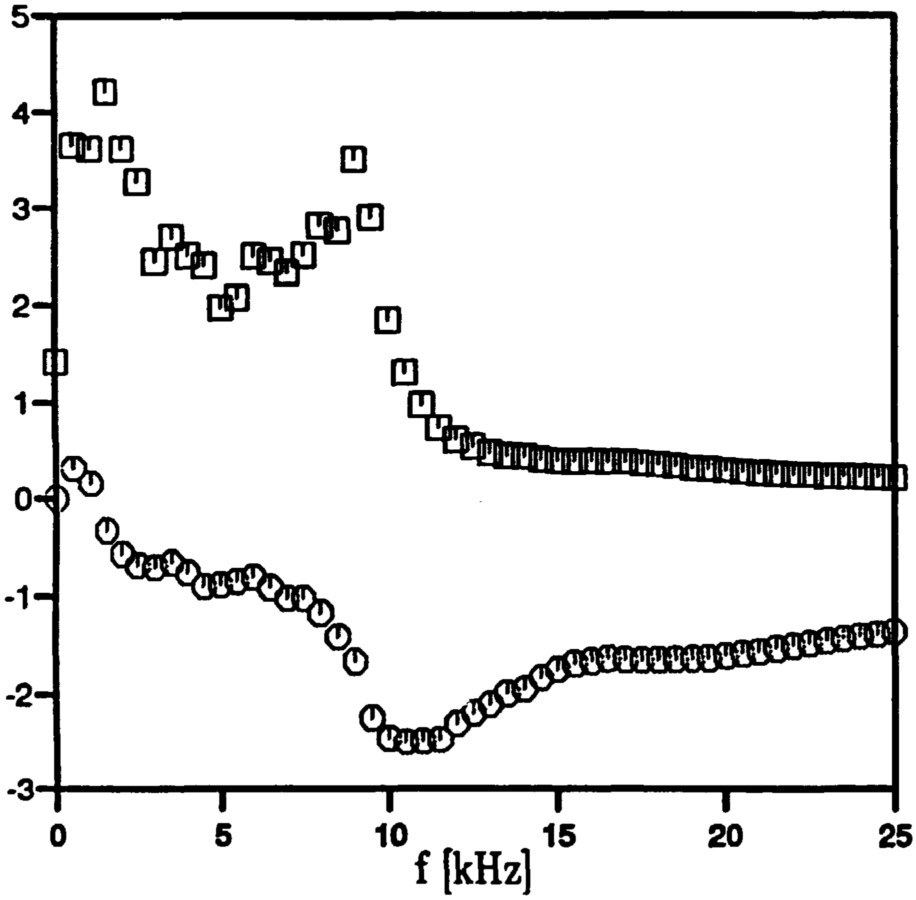

Figure 1. Cross-power spectrum for n and E. The amplitude spectrum $|S(f)|$ is shown in arbitrary units and indicated by squares. The frequency spectrum $\psi(f)$ is in radians and indicated by circles.

1) Huld, T., Nielsen, A. H., Pécseli, H. L., and Rasmussen, J. Juul. (1991). Phys. Fluids B3, 1609.

3.3 Fusion Plasma Physics

3.3.1 Theoretical considerations for fast ion and alpha-particle diagnostics for JET

(H. Bindslev)

It was hoped that the first experience with JET's fast ion and α-particle diagnostic (KE4) would have been gained in 1992 but this was severely limited by technological difficulties, chiefly with the gyrotron. The diagnostic was described briefly in the annual reports for 1990 and 1991 from the Optics and Fluid Dynamics Department.

On the theoretical front the main contributions were:

- The preliminary investigation of relativistic effects in reflectometry, reported last year, was extended and refined.
- A kinetic model of Thomson scattering is being developed and substantial progress has been made towards completing the model in the cold plasma limit. Discrepancies between this model and the long standing model based on a fluid description of the plasma have been found and explained by errors in the classical fluid derivation. The corrected fluid model is in agreement with the cold plasma limit of the kinetic model.
- A new numerical scheme for calculating the Shkarofsky functions was developed allowing the Shkarofsky functions to be evaluated in parameter ranges where the traditional method is unstable. (The Shkarofsky functions play the role of the plasma dispersion function in weakly relativistic plasmas). A consequence of this development is that ray tracing near perpendicular to the ambient magnetic field, which was previously hampered by numerical instabilities, can now be performed stably.

3.3.2 Studies of edge localised modes and associated fluctuations in JET with the multichannel reflectometry system

(A. L. Colton)

Fluctuations in most plasma quantities are observed in the plasma edge region of magnetically confined plasmas and are associated with a wide range of phenomena. Fluctuations of a continuous nature covering a wide frequency spectrum are thought to contribute to the enhanced radial transport of particles and energy which is observed in tokamaks, but this has so far not been conclusively proved. More specifically, a reduction in the fluctuation level of the edge plasma is thought to occur at the transition from L-mode to H-mode. During the H-mode edge localised modes (ELMs) are seen as discrete bursts of activity near to the separatrix. These ELMs perturb the density, temperature, and energy content of the plasma and generally lead to a decrease in energy confinement. However, recent experiments suggest that ELMs can be utilised as a means of controlling the plasma density and impurity level and thus prolonging the H-mode significantly. Prediction of both the mean and peak particle and energy loss from the plasma during ELMs is also necessary for the design and operation of a tokamak divertor. It is clear that a better understanding of the diverse fluctuation phenomena would benefit both the understanding of plasma physics and the fusion performance.

Fluctuations can be observed with many diagnostics. Microwave reflectometry is a method aimed particularly at the plasma edge that is at present being developed at JET. In a microwave reflectometer an electromagnetic wave is directed into the plasma and reflected when the plasma frequency equals the wave frequency. For a suitably polarised wave the location of the reflecting layer depends on the electron density, and so this technique can be used to observe density fluctuations. By correlating the signals from two reflectometers it is furthermore possible to observe the extent and propagation of density structures.

Two new methods for calibrating fixed frequency data have been developed to cope with problems caused by ELMs. The main results obtained are:

- The evolution in density gradient and profile in the edge region has been investigated during ELMs using two new techniques for calibrating fixed frequency phase data.
- A significant decrease in density gradient and a density pulse propagating outwards have been observed during the ELM.
- Measurements of density and magnetic fluctuation spectra show a quasi-coherent precursor oscillation prior to the ELM, and a period of broadband turbulence coinciding with the main D_α burst.
- For larger ELMs the precursor oscillation originates in the inner edge region and spreads outwards. For high frequency, low amplitude ELMs the precursors are localised to one channel only, at $n = 1.1 \times 10^{19}$ m^{-3}.
- The problem of whether the coherent detectors at JET are measuring phase or amplitude fluctuations in the reflected signal, depending on the absolute phase, has been addressed. The density related fluctuation signature of the ELMs is shown to be fairly independent of the absolute phase.

3.3.3 Reflectometer modelling

(P. Michelsen and H. L. Pécseli (University of Oslo, Norway))

Recently, microwave reflectometry has been of increasing interest for measuring plasma density profiles and plasma fluctuations, especially in fusion experiments. With two microwave beams of slightly different frequencies the density variations in two nearby positions can be monitored simultaneously, and by correlation technique information about the plasma fluctuations may be gathered. The beams are reflected at cut-off layers in the plasma. However, since the refractive index of the plasma is varying along the whole beam path, thereby changing the phase of the reflected signal, the interpretation of the measurements is difficult.

A model for the plasma turbulence has been derived and used for analytical calculation of the expected characteristic fluctuation velocity, and for correlation and crosscorrelation functions of the temporally varying phase of the measured signal. A numerical model has been developed in order to further investigate the possibilities of gaining the maximum information from a two-beam correlation reflectometer and also to illustrate the practical applicability. The phase variation of the microwave signal was calculated by solving the full wave equation using a numerical code COLSYS, which can solve boundary-value problems for mixed-order systems of ordinary differential equations.

The correlation technique gives results in terms of averaged velocities. We have demonstrated that a relatively simple method, extremum coincidence counting, can in a number of nontrivial cases give valuable additional information. Our results indicate that a two-frequency reflectometer can in a number of cases prove to be a versatile method for diagnosing local density fluctuations in fusion related plasma experiments. When the density perturbations have a velocity component in the direction defined by the probing electromagnetic wave beams, then this velocity component can be determined relatively accurately by a crosscorrelation of the modulated phase of the reflected waves, where the modulation is caused mainly by density perturbations through the reflection point (i.e. cut-off layer) for the waves.

3.3.4 Plasma equilibria calculated on the basis of magnetic compressive and tensile stresses

(V. O. Jensen)

It is well known that a magnetic field can be conceived as a medium where an isotropic compression stress, $B^2/2\mu_o$, is superimposed on a tensile stress, B^2/μ_o, parallel to the lines of force. When an ideal MHD plasma is present in the magnetic field, the particle pressure adds to the magnetic stresses to form a combined pressure tensor.

The work on using this concept to calculate and discuss certain properties of plasma equilibria has been continued through 1992. The main findings are:

- The virial theorem for an axisymmetric toroidal plasma can easily be derived and understood.
- Characteristic variations of the shapes of cross section of magnetic flux tubes with minor radius, r, in toroidal plasmas are easily found and understood.

3.4 Pellet Injectors

3.4.1 The multishot pellet injectors for FTU, Frascati, and RFX, Padova

(H. Sørensen, B. Sass, A. Michelsen, A. Petersen, K-V. Weisberg, and J. Bundgaard (Engineering and Computer Department))

For some years the pellet injector group has been working on the development of multishot pellet injectors for use at the tokamak FTU in Frascati near Rome and for the reversed field pinch RFX in Padova. The development work was performed under a contract with ENEA in Italy.

Terms for a contract covering design, manufacture, and installation of the two injectors were hereafter negotiated for some time. The contract for the multishot pellet injector for FTU, Frascati, was signed at ENEA in Rome in March and at Risø in April and the work officially started in April.

The design work was subsequently completed and the various parts for the injector were ordered/manufactured. In late November most parts for the injector had been delivered. Also most of the software for operation of the injector had been written.

The building of the 8-shot unit in which the pellets are formed and fired begun in November. The assembling of the injector started in December. It is planned to start operating the completed injector in March 1993 and to install the injector at FTU in June-July 1993.

The order for the injector for RFX in Padova was approved by ENEA in late September and the work was officially initiated in the beginning of November. The ordering and manufacturing of parts for the RFX injector were hereafter started. It is planned that the injector shall be installed at RFX in the beginning of 1994.

Apart from pellet sizes the RFX injector will be nearly identical to the FTU injector, and most of the work in connection with purchasing and manufacturing could be made by repeating the work in connection with on the FTU injector.

3.5 Participants in the Work in Continuum Physics

Scientific staff

Ellegaard, Ole (part time (25%))
Jensen, Vagn O.
Lynov, Jens-Peter
Michelsen, Poul
Nielsen, A. H.
Rasmussen, Jens Juul
Stenum, Bjarne
Sørensen, Hans
Weisberg, Knud-V.

Ph.D. students

Andersen, Annette (at present working at JET, U.K.)
Bindslev, Henrik
Hesthaven, Jan S.

Technical staff

Bækmark, Lars
Michelsen, Agnete
Nielsen, Mogens O.
Petersen, Andreas Dietrich (until 30 September)
Reher, Børge
Sass, Bjarne
Thorsen, Jess
Schmidt, Michel (3 August - 4 September; 30 November - 4 December)

Secretaries

Astradsson, Lone
Skaarup, Bitten
Toubro, Lene

Guest scientist

Karpmann, V. I., Izmiran, Moscow, Russia

Short-time visitors
Barratt, P., Riverside, USA
Coutsias, E. A., University of New Mexico, U.S.A.
Dalziel, S., University of Cambridge, U.K.
Koepke, M.E., West Virginia University, Morgantown, USA
Mezentsev, V. K., Inst. Automation and Electrometry, Novosibirsk, Russia
Pécseli, H. L., University of Oslo, Norway
Schrittwieser, R., Innsbruck University, Austria
Sutyrin, G., Institute of Oceanology, Moscow, Russia
Turitsyn, S. K., Inst. Automation and Electrometry, Novosibirsk, Russia

Ph.D. Degree

Bindslev, Henrik

3.6 Publications and Educational Activities

3.6.1 Publications

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Research in the Optics and Fluid Dynamics Department is performed within two sections. The Optics Section has activities within (a) optical materials, (b) quasi-elastic light scattering and diagnostics in solids, fluids and plasmas, and (c) optical and electronic information processing. The Continuum Physics Section performs (a) studies of nonlinear dynamical processes in continuum systems, (b) investigations of other problems in fusion plasma physics, and (c) develops pellet injectors for fusion experiments. Most of these activities are done in connection with the Euratom Association. A summary of activities in 1992 is presented.

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